UTILISATION OF REMOTE MONITORING TO EXAMINE PHYSICAL ACTIVITY, METABOLIC HEALTH, AND WELLBEING ACROSS THE PERINATAL PERIOD

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Abstract

It is well established that physical activity (PA) is beneficial for overall health and that physical inactivity increases the risk of development of type 2 diabetes mellitus (T2DM) and other lifestyle influenced, non-communicable long-term conditions. Importantly, glucose variability provides important prognostic insight for individual metabolic health prior to the onset of T2DM and provides valuable information pertaining to glucose control as a research methodology. Healthy metabolic processes adapt during pregnancy to adequately provide for the needs of the developing foetus. However, metabolic dysfunction during pregnancy can lead to gestational diabetes mellitus (GDM). Even though PA has been found to decrease the risk of GDM, many pregnant women fail to meet recommended PA guidelines.

Sport England report that between mid-November 2020 and 2021, 61.4% of adult achieved the recommended PA guidelines, whilst 27.2% of adults were defined as physically inactive (Sport England, 2021), which may have long term implications for the metabolic health of the population. Additionally, remote research methodologies that prevent face-to-face contact and virus transmission during the coronavirus 2019 (COVID-19) pandemic, whilst also increasing the reach and sample of participants are warranted. Continuous, device-derived measurement techniques, such as accelerometry and continuous glucose monitoring (CGM) allow the quantification of the duration and magnitude of daily PA and glucose control, respectively. Yet, the feasibility and acceptability of remote data collection for clinical value via these methods remains unknown.

The overarching aim of the body of work described in this thesis was to investigate the acceptability and feasibility of remote data collection to explore PA and glucose control

across the perinatal period. In addition, due to the timing of this data collection and the World events that were impacting habitual lifestyle and healthcare at the time, thematic analysis of semi-structured interviews sought to identify pregnant women's perceived barriers to antenatal exercise and the impact of the COVID-19 pandemic on the pregnancy experience.

Chapter 4 explored the feasibility and acceptability of remote data collection, in addition to the effectiveness of two home-based exercise interventions. Anthropometric data, blood samples, CGM, and PA data were collected remotely prior to and following a home-based exercise intervention incorporating i) mobile health (mHealth) technology and exercise counselling, or ii) online resources only. Semi-structured interviews to explore participant experiences were conducted pre- and post-intervention. Data provided novel evidence that remote testing is a feasible approach to obtain data, however further refinements were required to increase data availability. These adaptations were then implemented in *Chapter 5*. Moreover, low levels of intervention drop-out (16%), promising preliminary health outcome data, such as a greater increase in moderate-to-vigorous PA (MVPA) completed in 10-minute bouts (MVPA+10) in the mHealth group (58 min/wk; CI= -0.06, 0.98, d= 0.47) compared to the online resources group (14 min/wk, CI= -0.32, 0.54, d= 0.12) and positive participant perceptions reinforce the effectiveness of home-based exercise interventions, that incorporate individualised support and mHealth technology.

Chapter 5 utilised those remote testing techniques piloted in *Chapter 4* to determine the relationship between PA and glucose control across the perinatal period, disaggregated by trimester including postpartum, using objective continuous assessment methods. Forty-nine pregnant women underwent remote assessment of CGM and PA at trimesters 2 (T2) and 3 (T3), and within 6 weeks postpartum (T4). Glucose variability and PA patterns, as well as the relationship between glucose control and PA across the perinatal period were assessed. Findings firstly, demonstrated slightly higher levels of glucose variability during pregnancy in comparison to postpartum, whereby 24-hour variability decreased, albeit non-significant, between postpartum and T2 (mean difference: -2.15%; CI= -4.52, 0.23; P=0.08) and decreased from postpartum and T3 (mean difference: -2.45%; CI= -4.69, -0.21; P=0.03). Secondly, there was an increase in total (mean difference: 53:45 min; CI= 0.72, 106.79; P=0.11) and light (mean difference: 48:13 min; CI= 15.77, 80.70; P=0.004) PA levels from T2 to T4, with no change in moderate-to-vigorous PA (MVPA) (P>0.05). Finally, there was no relationship between 24-hour or daytime glucose control and PA at any timepoint. Notably, participants recorded low levels of PA at all timepoints, which may have hindered power to detect any relationship. Importantly, novel data demonstrating a decrease in glucose variability at postpartum in comparison to during pregnancy should be noted and may be linked to physiological and behavioural changes (e.g. changes in insulin response during pregnancy or breastfeeding) that occur across the perinatal period.

Chapter 6 collected rich, in-depth qualitative data to contextualise findings in *Chapter 5* and reflect women's perceived barriers to antenatal exercise during COVID-19 (question 1) and their perceptions of the pregnancy experience during COVID-19 (question 2). Questionnaires reporting anxiety, depression and PA levels were completed by all participants (n=14). Semi-structured interviews were conducted between November 2020 and May 2021. Interviews were analysed using thematic analysis for each research question, individually, to provide two sources of information. Question 1 revealed four main themes: '*Perceptions of being an active person shaping activity levels in pregnancy', 'How do I know what is right? Uncertainty, seeking validation and feeling informed',* *‘Motivators to antenatal exercise’* and *‘A process of adaptations and adjustment’*. Question 2 also revealed four main themes: *‘Navigating changes to healthcare delivery and antenatal care’, ‘Adapting to lifestyle changes’, ‘Decision making in the context of COVID-19’,* and *‘Seeking support during COVID-19’*. The findings of the study highlighted the importance of direct psychosocial support and clear, trustworthy information for pregnant women. Findings also support the fundamental need for better education amongst healthcare professionals regarding antenatal exercise.

Collectively, the data contained within this thesis support the feasibility of remote data collection and remote exercise interventions that include mHealth technology. This highlights the potential use of such tools in healthcare to provide clinical exercise physiology support in an economically viable manner. Data revealed increased glucose variability during T2 and T3, accompanied by low levels of PA during healthy pregnancy. Nonetheless, no relationships between PA and glucose variability across the perinatal period were observed, suggesting that physiological and behavioural changes occurring across gestation may impact glucose variability. Finally, qualitative data revealed themes of uncertainty around exercise and PA during pregnancy which highlights the importance of psychosocial support for pregnant females and education for healthcare professionals (HCPs) regarding ante- and post-natal exercise. Although these data were collected during the COVID-19 pandemic, the application of findings transcends this timeframe.

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Declaration

I declare that the work within this thesis is entirely my own.

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List of Abbreviations

Abbreviation	Title
ADA	American Diabetes Association
AU	Arbitrary Units
BMI	Body Mass Index
CGM	Continuous Glucose Monitoring
COVID-19	Coronavirus Disease 2019
CRF	Cardiorespiratory Fitness
CV	Coefficient of Variation
CVD	Cardiovascular Disease
DBP	Diastolic Blood Pressure
ENMO	Euclidean Norm Minus One
GAD-7	Generalised Anxiety Disorder-7 Scale
GDM	Gestational Diabetes Mellitus
GGIR	Open-source R Software Package
GLUT-1	Placental Glucose Transporter
GLUT-4	Glucose Transporter Protein Type 4
GWG	Gestational Weight Gain
HbA_{1c}	Glycated Haemoglobin
HCP	Healthcare Professional
HDL	High Density Lipoprotein
HOMA-IR	Homeostatic Model Assessment for Insulin Resistance
HR	Heart Rate
HRA	Health Research Authority
IMD	Indices of Multiple Deprivation
IPAQ	International Physical Activity Questionnaire
LDL	Low Density Lipoprotein
MAP	Mean Arterial Pressure
MARD	Mean Absolute Relative Difference
MET	Metabolic Equivalent of Task
mHealth	Mobile Health
MVPA	Moderate-Vigorous Physical Activity
NICE	National Institute for Health and Care Excellence
NIH	National Institute of Health
NHS	National Health Service
OGTT	Oral Glucose Tolerance Test
PA	Physical Activity
PARQ+	Physical Activity Readiness Questionnaire
PHQ-9	Patient Health Questionnaire 9
RCT	Randomised Controlled Trial
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SBP	Systolic Blood Pressure
SD	Standard Deviation
SE	Standard Error
SVM	Signal Vector Magnitude
T2DM	Type 2 Diabetes Mellitus

TAR	Time Above Range
TBR	Time Below Range
TIR	Time In Range
$\dot{V}O_{2max}$	Maximal Oxygen Uptake
WHO	World Health Organisation

List of Definitions

Term	Definition
Perinatal Period	Refers to pregnancy and the first 12 months following childbirth.
Postpartum	Is the time after childbirth. The postpartum period begins upon birth of the infant, whilst the end is less well defined, but often considered the 6-8 weeks after birth.
Antenatal	Refers to the period of time during pregnancy.
Parity	Indicates the number of deliveries (including live births and stillbirths) where pregnancy reached viable gestational age (~24 weeks gestation).
Primiparous	An individual bearing (or that has borne) one offspring.
Multiparous	An individual having borne more than one child.
Glucose Variability	Refers to oscillations in blood glucose levels that occur throughout the day.
Glucose Control	Refers to maintenance of normal blood glucose levels (4-5.4 mmol/L fasting glucose, <7.8 mmol/L 2 hours postprandial).
Glucose Tolerance	Refers to the ability to dispose of a glucose load, typically measured via oral glucose tolerance test.
Glucose Intolerance	Refers to an impaired ability for glucose disposal.
Glucose Homeostasis	Refers to the balance of insulin and glucagon to maintain blood glucose control.
Coefficient of Variation	Is a calculation to achieve a percentage by dividing the standard deviation by the mean glucose and multiplying by 100.
Validity	A test is valid if it measures what it claims to measure.
Feasibility	Refers to the possibility that task/goal can be achieved reasonably.
Reproducibility	Refers to the ability to be reproduced or copied.

CHAPTER 1: INTRODUCTION

1.1. Thesis Structure

This thesis is organised into 7 chapters. *Chapter 1* provides a brief introduction and background to the PhD, and outlines the primary aims and objectives. *Chapter 2* goes on to provide a critical review of existing literature, as well as rationale for the empirical research study chapters that follow. *Chapter 3* describes the general methods utilised in *chapters 4 and 5*. *Chapters 4, 5 and 6* detail three empirical research studies that form the main body of this thesis. Each research study includes a brief and specific introduction related to the aim of the study, a description of the employed methods, presentation of the results, and a critical discussion of the findings in relation to previous literature. *Chapter 7* synthesises key findings from the PhD and proposes implications of the research and recommendations for future directions.

1.2. Background

There are two major themes within this thesis: remote data collection and pregnancy. Remote testing involves participants collecting and/or recording their own health outcomes from home. Home-based monitoring and use of remote devices can ensure data collection from a large sample of participants (i.e., nationwide) at a low-cost. The COVID-19 pandemic necessitated the utilisation of remote data collection for research yet possesses a multitude of further benefits. Remote data collection enables insight into participant's habitual lifestyles rather than assessment in controlled laboratory conditions. This provides real-world data with translational value. One overwhelming positive of using this approach is that evidence from clinical trials suggest that minimisation or, indeed, elimination of research facility visits may enhance participation for some minority groups traditionally underrepresented in research, for example those from diverse ethnic, low socioeconomic, or rural backgrounds (Noonan and Simmons, 2021). Yet, it is currently unknown whether remote clinical trials are feasible and can provide an effective data collection alternative to laboratory testing. Therefore, **objective 1** of this thesis is to examine the feasibility and acceptability of remote data collection of health outcomes.

There is a plethora of evidence supporting the efficacy of PA in the prevention and amelioration of lifestyle-related health conditions (Drenowatz et al., 2016, Lee et al., 2012). The current UK evidence-based PA guidelines recommend 150 minutes of moderate intensity PA or 75 minutes of vigorous intensity PA per week (Chief Medical Officers, 2019). Despite the known benefits of PA, only 61.4% of adults achieved the recommended guidelines per week between mid-November 2020 and mid-November 2021 (Sport England, 2021) where 63.3% of adults were meeting the recommended guidelines. Moreover, the COVID-19 pandemic led to significant changes in PA levels of the population. The prevalence of adults achieving the recommended PA guidelines decreased by 1.9% in 2020-2021 compared to pre-pandemic (November 2018-2019) (Sport England, 2021). Specifically, a 37% reduction in weekly minutes of PA was observed from the week before the first case of COVID-19 in the UK was announced to the first week of COVID-19 restrictions (McCarthy et al., 2021). Furthermore, 63% of people reported decreasing their activity in the first week of COVID-19 restrictions (McCarthy et al., 2021). Based on this, many academics and healthcare professionals fear that one of the long-term effects of the COVID-19 pandemic will be the exacerbation of lifestyle related conditions, but this longitudinal data is not yet available.

Previous research studies aiming to increase PA levels, specifically exercise, in previously sedentary individuals without supervision from a health professional have reported poor adherence (Jung et al., 2020, Hesketh et al., 2021, Roy et al., 2018). Poor adherence and compliance to prescribed exercise significantly impacts on the ability to positively change clinical outcomes. A need for novel and innovative interventions to improve adherence and compliance has been noted previously (Hesketh et al., 2021). A common barrier to exercise is time (Scott et al., 2020), therefore in addition to the suspension of non-essential research within research facilities, this led to the development of a home-based exercise intervention, supported by mHealth technology. It was hypothesised that this could be an effective method to increase PA levels and enhance adherence to exercise during COVID-19 due to the elimination of face-to-face contact. However, the feasibility and acceptability to a remote, home-based intervention to increase PA during COVID-19 is unknown. Accordingly, **objective 2** is to examine the feasibility and acceptability of a home-based exercise intervention, supported by mHealth technology.

Females experience significant physiological variation throughout their lifespan, underpinned by fluctuating levels of reproductive hormones. Pregnancy is a dynamic process whereby profound changes in reproductive hormones and physiological adaptation occur to support a growing foetus. Gestational Diabetes Mellitus (GDM) affects 5.4% of pregnancies in Europe (Eades et al., 2017) and is associated with obesity, maternal age of first pregnancy, high calorie diets and low levels of PA (Ramos-Leví et al., 2012). An estimated 10% of females who have GDM during pregnancy will develop T2DM soon after delivery, while 20-60% of females will present with it in the 5-10 years after birth (Buchanan et al., 2012). Glucose control during the perinatal period is critical for foetal health and research has demonstrated that glucose variability during pregnancy can adversely affect foetal development (Law et al., 2015, Murphy, 2019, Kristensen et al., 2019). Limited data exists regarding glucose variability across the perinatal period in healthy females. Given this lack of understanding and to gain insight, **objective 3** of this thesis is to examine glucose control across the perinatal period in healthy pregnant females.

PA has been demonstrated to have beneficial effects on glucose control in healthy pregnancy (Gradmark et al., 2011) and has been associated with a decreased risk of developing GDM (Aune et al., 2016). Pregnant females, likewise to their non-pregnant counterparts, are recommended to perform 150 minutes of moderate intensity PA per week (Mottola et al., 2018, UK Chief Medical Officers, 2017). That said, a reduction in self-reported levels of PA during pregnancy, that have persisted at 6 months postpartum, have been previously observed (Pereira et al., 2007). Yet, whether a similar pattern across the perinatal period during COVID-19 pandemic restrictions is worthy investigation. Therefore, **objective 4** is to objectively quantify PA levels across the perinatal period in healthy pregnancy during the COVID-19 pandemic. Furthermore, whether PA levels influence glucose control across the perinatal period requires exploration. Recent literature has identified a strong relationship between PA and glucose control in healthy pregnant females (Behravesh et al., 2021), though trimester-specific differences in maternal glucose excursions have been observed (Law et al., 2015). Whether this relationship exists to comparable extents across the perinatal period, disaggregated by trimesters and postpartum, remains unknown. Therefore, **objective 5** is to assess the relationship between PA and glucose control across the perinatal period to understand whether gestational age plays a role in the relationship, using objective CGM.

Despite the known benefits of antenatal PA and exercise, pregnancy is often characterised by a substantial decrease in exercise levels (Campbell and Mottola, 2001, Pereira et al., 2007). Several studies have explored pregnant female's experiences of and barriers to antenatal PA. However, the COVID-19 pandemic may have exacerbated barriers to antenatal exercise and PA. A large online survey of 900 pregnant and recently postpartum females in Canada found that 64% of females reported reduced PA with the onset of isolation measures (Davenport et al., 2020). Therefore, **objective 6** is to understand perceived barriers to antenatal exercise during the COVID-19 pandemic. Additionally, the COVID-19 pandemic has had a substantial psychological impact on the mental health of pregnant females (Saccone et al., 2020) and elevated anxiety and depression levels have been reported (Lebel et al., 2020). Pregnant individuals who reported high PA levels have been shown to have lower scores for anxiety and depression measures during the COVID-19 pandemic restrictions (Davenport et al., 2020, Lebel et al., 2020). This emphasises the importance of PA and exercise during pregnancy and the significant impact of COVID-19 on pregnant female's lives. Finally, **objective 7** of this thesis is to explore perceptions of the pregnancy experience during the COVID-19 pandemic.

1.3. Aims

The aims of this thesis are to:

1. Examine the feasibility and acceptability of remote data collection and a home-based exercise intervention, supported by mHealth technology.
2. Investigate the relationship between glucose variability and PA across the perinatal period, using objective continuous assessment methods.
3. Explore pregnant female's perceived barriers to antenatal exercise and the impact of the COVID-19 pandemic on the pregnancy experience.

1.4. Objectives

The aims outlined above will be achieved through the following objectives.

To address Aim 1:

1. Examine the feasibility and acceptability of remote data collection

2. Examine the feasibility and acceptability of a home-based exercise intervention supported by mHealth technology**.**

To address Aim 2:

3. Examine glucose control across the perinatal period in healthy pregnant females.
4. Report PA levels across the perinatal period in healthy pregnancy during the COVID-19 pandemic.
5. Assess the relationship of PA and glucose control across the perinatal period, using objective continuous assessment methods.

To address Aim 3:

6. Conduct semi-structured interviews with pregnant females to understand perceived barriers to antenatal exercise during the COVID-19 pandemic**.**
7. Explore perceptions of the pregnancy experience during the COVID-19 pandemic.

CHAPTER 2: LITERATURE REVIEW

2.1. PA & Metabolic Health

2.1.1. Physical Activity and Health

In the UK, PA consensus guidelines recommend that adults aged 18-64 years perform at least 150 minutes of moderate-intensity PA or 75 minutes of vigorous intensity PA per week, in addition to muscle-strengthening activities on at least two days per week (Chief Medical Officers, 2019). PA has been demonstrated to reduce the risk of obesity, hypertension, T2DM and cardiovascular disease (CVD) (Ekelund et al., 2011, Manson et al., 2002, Tuomilehto et al., 2001, Hahn et al., 2009) and, accordingly, physical inactivity is the fourth leading cause of death, worldwide (Kohl III et al., 2012). Yet, UK statistics report that only 61.% of adults meet the recommended guidelines, whilst 27.2% of adults are physically inactive (less than 30 minutes of moderate-intensity PA per week) (Sport England, 2021). Worldwide, 75% of adults meet the recommended PA guidelines (World Health Organization, 2019). Notably, the Global Action Plan of PA by the World Health Organisation (WHO) reports that as countries develop economically, levels of inactivity increase (World Health Organization, 2019), perhaps explaining the lower levels of PA reported in the UK in comparison to globally. The increase in physical inactivity in developed countries is suggested to be due to changing patterns of transportation, increased use of technology and urbanisation (World Health Organization, 2019). Consequently, health disorders associated with high physical inactivity prevalence, including health-related quality of life, as well as direct and indirect economic costs, exert a substantial burden on societies and respective health systems (Ding et al., 2016).

2.1.2. Physical Activity and Exercise Terminology

Although sometimes used interchangeably, PA and exercise are terms that have distinct and important differences. These terms are utilised throughout the thesis and, therefore, these distinctions are important to note. PA refers to any bodily movement produced by skeletal muscles that requires energy expenditure (World Health Organisation, 2020). This term includes all movements during leisure time, though moderate- and vigorous-intensity PA, specifically, have been shown to improve health. Exercise, conversely, is a domain of PA that is structured, repetitive and has a final or an intermediate objective to improve or maintain physical fitness (Caspersen, Powell & Christenson, 1985). Interventions targeted at increasing PA and structured exercise levels may improve rates of disease prevalence and therefore warrant investigation.

2.1.3. Glucose Metabolism

Glucose is fundamental for energy consumption and serves as the primary metabolic fuel in humans. Glucose metabolism involves many processes, including the different pathways of glycolysis and glycogen synthesis (Figure 2.1). The body's blood glucose concentration frequently changes in response to fasting and consumption, yet blood glucose is closely regulated via a feedback mechanism. For example, following a meal, there is a rise in blood glucose, which simultaneously stimulates insulin secretion. Insulin is a hormone that regulates glucose levels in the blood and is produced from the pancreas. Insulin secretion causes glucose to be deposited in the liver as glycogen. Post-meal, blood glucose concentration gradually reduces, stimulating the liver to release glucose back into the blood. In contrast, a reduction in blood glucose concentration stimulates glucagon secretion, which raises blood glucose levels (Nakrani et al., 2020). Optimal glucose metabolism is dependent on an individual's physiological and nutritional conditions as well as physical fitness (Tarnopolsky and Ruby, 2001). Poor glucose metabolism leads to metabolic dysfunction including T2DM (Nakrani et al., 2020).

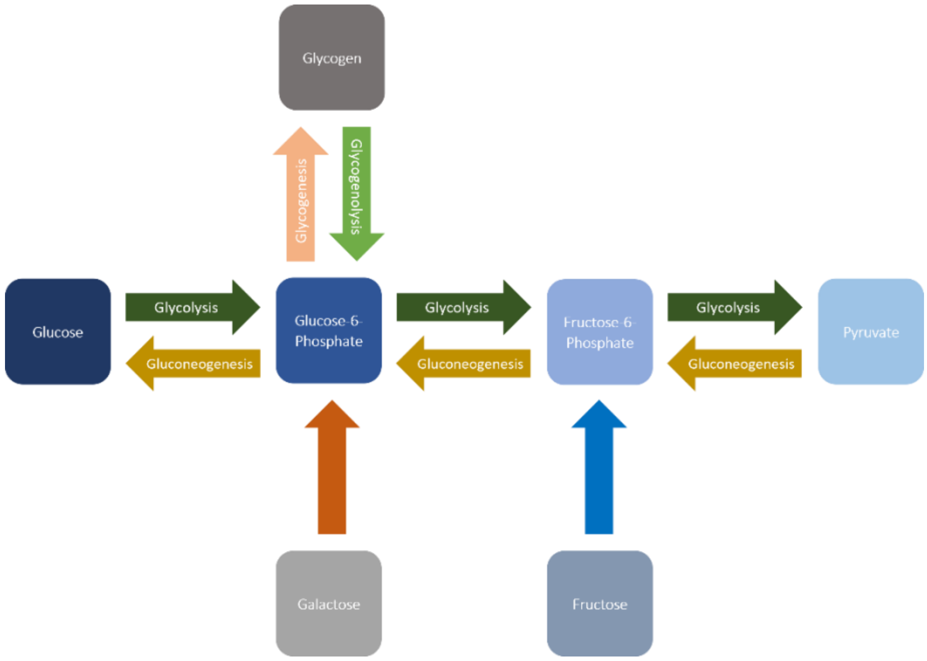

Figure 2.1 The processes of carbohydrate metabolism, including glycolysis, gluconeogenesis, glycogenesis, glycogenolysis, fructose metabolism, and galactose metabolism. Adapted from Nakrani, Wineland and Anjum (2021).

Glucose variability refers to the oscillations in glucose concentration levels that occur throughout the day. High variability in glucose concentration may occur due to physiological dysfunction, but also due to the circadian rhythm of endogenous hormones, nutritional intake, or PA (Wang et al., 2012). Despite, glucose variability being observed in healthy individuals with normal glucose tolerance, variability is magnified in sedentary, overweight, or obese individuals (Salkind et al., 2014). Moreover, higher glucose variability has been reported in obese adults who have normal glucose tolerance (Salkind et al., 2014). Therefore, glucose variability provides important early-stage insight for individual metabolic health and warrants investigation in all research examining glucose control.

2.1.4. Physical Activity and Glucose Metabolism

It is well established that PA is beneficial for overall health and that physical inactivity increases the risk of development of T2DM and CVD (Chan et al., 2004). Multiple linear regression analysis, conducted by Swindell and colleagues (2018), revealed that MVPA

(95%CI -0.128, -0.027), as well as total PA (95%CI -0.194, -0.107), were negatively associated with Homeostatic Model Assessment for Insulin Resistance (HOMA-IR) in adults with prediabetes (*n*=2326). It is postulated that individuals participating in a greater amount of PA have increased insulin-stimulated glucose control and skeletal muscle glucose disposal in comparison to individuals performing less PA (Hollenbeck et al., 1985). Furthermore, just a single bout of acute exercise has been demonstrated to increase glucose uptake into skeletal muscle (Pruett and Oseid, 1970, Wang et al., 2013), which can persist hours after completion (Devlin et al., 1987, Mikines et al., 1988). Yet, there is little research examining the effect of PA on glucose variability.

2.1.5. Measurement of Glucose Metabolism

There are several tests that can be utilised to screen for impaired glucose metabolism and diagnose T2DM or GDM.

2.1.5.1. HbA1c

To measure a 2-to-3-month average of an individual's glycaemic control, glycated haemoglobin (HbA_{1c}) is frequently analysed and may be used to forecast the risk of diabetic complications (Schnell et al., 2017).

2.1.5.2. Fasting Plasma Glucose

Fasting plasma glucose may also be quantified. During fasting, glucagon is synthesised and subsequently plasma glucose concentration is increased. Insulin will then be produced to rebalance these increased glucose levels in healthy individuals, yet in people with T2DM or GDM, either not enough insulin is produced, or the body is not able to use the insulin effectively and therefore fasting glucose will be increased.

2.1.5.3. Oral Glucose Tolerance Test

An oral glucose tolerance test (OGTT) is another popular test that may be employed to examine glucose metabolism. This test consists of an orally consumed glucose challenge and subsequent plasma glucose measurements. Pregnant females who have a family history of T2DM or GDM, or those who present with raised fasting blood glucose levels are typically screened for GDM using an OGTT (Garrison, 2015).

2.1.5.4. Continuous Glucose Monitoring

An alternative way to measure glucose is the novel methodology of CGM, which allows continuous real-time measurements of glucose levels spanning an extended period of time (Yogev et al., 2004).

In contrary to the measurement of HbA_{1c}, CGM allows researchers to identify the intra- and inter-day glycaemic excursions that may lead to hypoglycaemia or postprandial hyperglycaemia (Danne et al., 2017). Measurement of HbA_{1c} is also an unreliable measure in patients with anaemia (National Institute of Diabetes and Digestive and Kidney Diseases, 2014), iron deficiency (Ford et al., 2011) and during pregnancy, due to the fluctuating glucose levels that occur throughout gestation (Nielsen et al., 2004). To utilise a CGM, the monitor is inserted into the interstitial fluid on the individual's tricep or stomach area and allows the quantification of the duration and magnitude of glycaemic excursions that occur during an individual's typical day. The individual is able to wear this monitor for 14 days and no calibration is required by the user (Rodbard, 2016). Despite the advantages of CGMs in the measurement of glucose control, use remains limited due to high cost, short sensor lifetimes and a lag time of interstitial fluid glucose relative to blood glucose (Rodbard, 2016). Though, as technology continues to advance, it is expected that utilisation of CGM measurements to analyse glucose control will increase in popularity (Rodbard, 2016). Beck and colleagues (2017) plotted mean glucose measured with CGM (Dexcom Inc, San Diego, CA) versus HbA_{1c} in 387 participants in three RCTs. They demonstrate that HbA_{1c} may commonly under-, or overestimate mean glucose. Yet, Yamada and colleagues (2020) found a significant correlation between HbA_{1c} and CGM levels when using the FreeStyle Libre Pro device with 59 participants. These findings highlight the need for high quality equipment paired with individualised data interpretation for each participant to assess an individual's glucose control.

2.2. Pregnancy

2.2.1. Symptoms of pregnancy

Pregnancy is typically defined as 40 weeks from the first day of a female's last period and is divided in to 3 trimesters (trimester 1 (T1), week 1-12; trimester 2 (T2), week 13-28; trimester 3 (T3), week 29-40). Whilst 40 weeks is the usual pregnancy time frame, a full-term baby can be born within 37-42 weeks.

2.2.2. Physiological Adaptations to Pregnancy

As well as symptoms such as nausea, fatigue and musculoskeletal pain, pregnant females experience vast physiological changes to support the needs of the growing foetus. These changes include cardiovascular adaptations such as an increase in cardiac output and maternal blood volume by up to 50%, compared with pre-pregnancy values (Skow et al., 2017) and metabolic adaptations such as increased protein content in body tissue and weight gain (Perales et al., 2019). Additionally, a large change in hormones occurs throughout pregnancy and postpartum (see Figure 2.2). In some cases, a lack of physiological changes during pregnancy may present complications or pathologies. This lack of changes can result in short-term complications, such as preeclampsia and GDM. Yet, these complications present during pregnancy are associated with an increased risk of CVD in later life. Though, antenatal PA has been demonstrated to produce beneficial effects for maternal and offspring health, specifically metabolic health, and mental wellbeing.

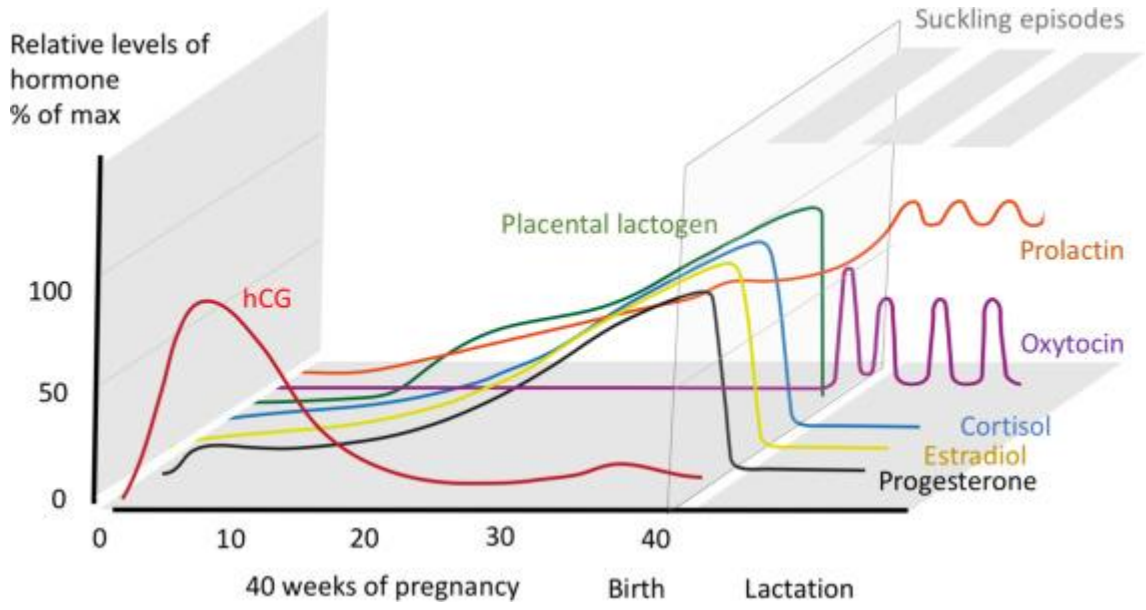

Figure 2.2 Diagrammatic representation of hormone changes during human pregnancy. (Grattan & Ladyman, 2020).

2.2.3. Metabolic Adaptations to Pregnancy

2.2.3.1. Glucose Control in Pregnancy

Normal metabolic processes must be altered during pregnancy to adapt to the needs of the developing foetus. In healthy pregnant females, insulin sensitivity decreases at 12-14 weeks through 36 weeks' gestation (Catalano et al., 1999). T1 and T2 are characterised by insulin resistance, with an approximate 50% decrease in insulin mediated glucose disposal (assessed by the hyperinsulinemic-euglycemic clamp technique) and a 200-300% increase in the insulin response to glucose (Catalano et al., 1999). This increased insulin response to glucose is required to meet the metabolic demands of the foetus, which needs 80% of its energy as glucose. In T3, the placental and foetal demands for glucose are approximately 150 grams per day (Lain and Catalano, 2007). Insulin resistance during pregnancy is also caused by a decrease in glucose transporter protein 4 (GLUT-4) expression within the maternal adipose tissue in T3, in addition to a decreased translocation of GLUT-4 to the plasma membrane in the skeletal muscle (Okuno et al., 1995).

Glucose is the primary source of energy for the growing foetus and is transported to the foetus in direct proportion to maternal glucose levels. Placental glucose transporter (GLUT-1) concentration is increased during pregnancy, facilitating the transplacental glucose flux, without evidence of maternal hyperglycaemia (Illsley, 2000). Previous studies have found fasting blood glucose levels to decrease during early pregnancy (Riskin-Mashiah et al., 2011). Throughout the remainder of gestation, studies have showed disparity in results. The majority of studies show a further decline in plasma glucose between the T1 and T2 (Lind et al., 1973, Mills et al., 1998, Victor, 1974), whilst others report no change (Afolabi et al., 2003, Siegmund et al., 2008). Again, some studies observed further decreases in plasma glucose between the T2 and T3 (Lind et al., 1973, Victor, 1974) whilst others reported no decrease (Afolabi et al., 2003, Sacks et al., 1995) or even a small increase (Mills et al., 1998, Siegmund et al., 2008). These heterogenous data are likely due to differing measurement methods, for example glucose collected fasted (Afolabi et al., 2003, Sacks et al., 1995, Lind et al., 1973, Riskin-Mashiah et al., 2011, Mills et al., 1998) or free-living (Parretti et al., 2001, Siegmund et al., 2008), or using hand-held glucose monitors (Parretti et al., 2001, Afolabi et al., 2003), OGTT (Lind et al., 1973, Sacks et al., 1995) or CGM (Siegmund et al., 2008). Participant characteristics (e.g. weight, activity levels, or diet consumption) are also likely to influence results between studies. Siegmund and colleagues (2008) observed a slight increase in blood glucose levels (n=32), measured using CGM for periods of 72 hours throughout pregnancy, and reported significantly higher values at week 36 of gestation. At 6 weeks postpartum, blood glucose levels remained similar to week 36 of gestation (Figure 2.2).

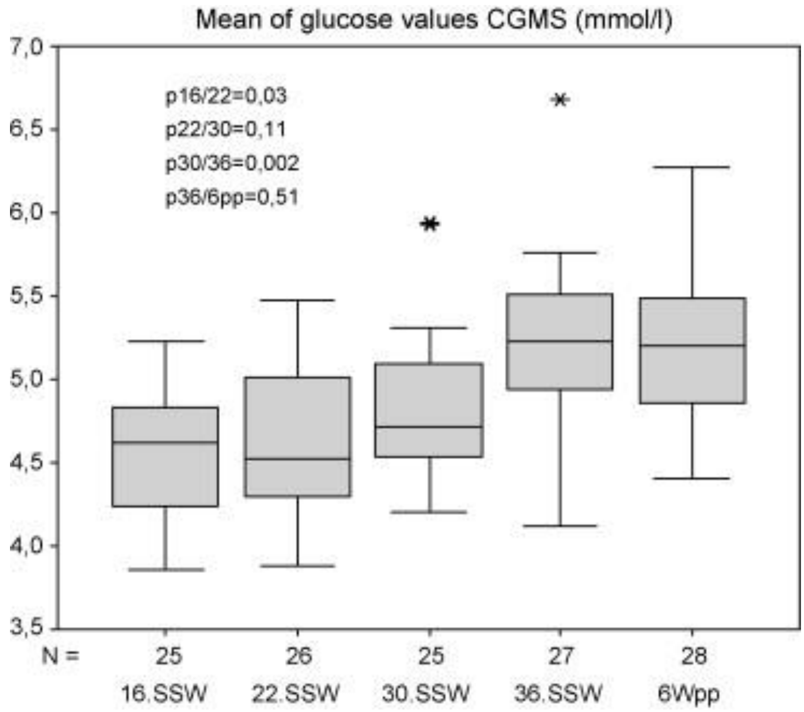

Figure 2.3 Mean glucose levels (mmol/L in *n*=32) at 16th (16.SSW), 22nd (22.SSW), 30th (30.SSW) and 36th (36.SSW) weeks of gestation, and at 6 weeks postpartum (6Wpp) measured using CGM (Siegmund et al., 2008).

GDM is characterised by glucose intolerance that begins or is first diagnosed during pregnancy and usually resolves shortly after delivery (Reece, 2010). As previously stated, an OGTT is typically utilised to diagnose GDM in pregnant females at 24-28 weeks' gestation. Females are offered this screening procedure for GDM if they possess risk factors such as a high body mass index (BMI), parental case of diabetes, or family origins are South Asian, Chinese, African-Caribbean or Middle Eastern. Diagnosis of GDM is critical for short- and long-term consequences affecting both the mother and child; These include not only pregnancy and delivery risks, but also future risk of T2DM, obesity, metabolic, cardiovascular, neurological and psychiatric problems in the mother (Metzger, 2007).

2.2.4. Mental Wellbeing in Pregnancy

Pregnancy is potentially a vulnerable period for a female's mental health due to pregnancy symptoms and the impending transition to parenthood. It has been estimated that approximately 9-13% of pregnant females experience depression (Evans et al., 2001, Gavin et al., 2005, Redshaw and Henderson, 2013) and approximately 13-15% of pregnant females experience anxiety (Heron et al., 2004, Henderson and Redshaw, 2013). Many perinatal mental health difficulties begin in pregnancy, and most of these are anxiety based (Howard and Khalifeh, 2020). Mental health difficulties during pregnancy may be attributed to a plethora of physiological, psychological, and sociocultural determinants. Firstly, the rapid transformation in hormone levels, namely the increase in the number of oestrogen and progesterone receptors, occurs during the first trimester. These changes in hormones affect the neurotransmitter systems of serotonin, dopamine and norepinephrine, which may contribute to the development of emotional disorders (Poudevigne and O'Connor, 2006). Secondly, the first trimester is commonly accompanied by a fear of miscarriage (Gong et al., 2013). Typically, females experience a stabilisation of emotions during the second trimester (Kołomańska et al., 2019). However, a renewed increase in anxiety levels tends to occur in the third trimester due to the approaching delivery (Kołomańska et al., 2019). Finally, it has also been suggested that changes in external appearance may decrease female's physical self-esteem, which may also influence the development of depression (Poudevigne and O'Connor, 2006). Overall risk factors for both antenatal anxiety and depression include social isolation, perceived low social support, poor relationship with partner, being aged under 18, living in a deprived area, and unplanned pregnancy (Littleton et al., 2007, Robertson et al., 2004, Leigh and Milgrom, 2008, Lee et al., 2007).

Mental wellbeing during pregnancy is a significant public health problem. Antenatal anxiety and depression negatively impact maternal quality of life. Furthermore, there is evidence supporting that exposure to stressful environments and poor mental health during pregnancy can adversely affect perinatal outcomes, such as infant emotional, and behavioural development (O'Connor et al., 2002). A study using UK primary care data reported that the proportion of children exposed to maternal mental health difficulties increased from 22.2% between 2005-2007 to 25.1% between 2015 and 2017 (Abel et al., 2019). Therefore, interventions to mitigate the risk of developing mental health difficulties during pregnancy are paramount.

2.2.4.1. Anxiety in Pregnancy

High levels of antenatal anxiety are significantly associated with adverse perinatal outcomes, such as preterm and spontaneous preterm birth, low birth weight, earlier gestational age, small for gestational age, and smaller head circumference at birth (Grigoriadis et al., 2018). Several potential explanations whereby anxiety leads to adverse perinatal outcomes have been proposed. Firstly, females who experience anxiety during pregnancy may be more likely to smoke, drink alcohol, or not attend antenatal healthcare appointments, which in turn increase the risk of adverse perinatal outcomes (Istvan, 1986, Paarlberg et al., 1995). Secondly, it has been proposed that an increase in stress hormones during pregnancy may lead to decreased uterine blood flow and consequently, induction of preterm labour (Istvan, 1986, Paarlberg et al., 1995, Johnson and Slade, 2003). Changes in immunologic functioning due to anxiety may also increase vulnerability to immune-modulated preeclampsia and preterm labour (Paarlberg et al., 1995).

2.2.4.2. Depression in Pregnancy

Furthermore, it has been found that the prevalence of depressive symptoms in pregnancy are significantly positively associated with preterm birth (Fransson et al., 2011, Li et al., 2009, Niemi et al., 2013, Straub et al., 2012). Antenatal depression has also been identified as a risk factor for low birth weight (Niemi et al., 2013, Grote et al., 2010) and small for gestational age babies (Jarde et al., 2016, Szegda et al., 2017). Despite scientific evidence supporting the association between antenatal depression and adverse perinatal outcomes, the associations are not consistent (Pampaka et al., 2021). Given inconsistent findings and limited evidence, further research is required to examine the association between maternal depression and perinatal outcomes. Research suggests that the effects and prevalence of maternal anxiety on perinatal outcomes are potentially more pressing and require intervention (Grigoriadis et al., 2018, Lee et al., 2007).

2.2.5. Physical Activity and Pregnancy

In the absence of contraindications antenatal exercise is recommended (Mottola et al., 2018). PA during pregnancy has been shown to decrease the risk of pre-eclampsia, GDM, caesarean delivery, instrumental delivery, excessive gestational weight gain (GWG), and a decreased severity of depressive symptoms and lumbopelvic pain (Mottola et al., 2018). Antenatal exercise has also been demonstrated to reduce the CVD risk in later life for both the mother (Clapp III, 2008) and offspring (May et al., 2016, May et al., 2010, May et al., 2014, May et al., 2012). Pregnancy-specific exercise guidelines in the UK recommend pregnant individuals to accumulate at least 150 minutes of moderate-intensity PA per week, incorporating both aerobic and strength training, over 3 days (UK Chief Medical Officers, 2017). For pregnant females who are not currently meeting these guidelines, a progressive adjustment towards them is recommended, whilst those who are already meeting the guidelines are instructed to continue throughout pregnancy. Absolute contraindications to exercise during pregnancy include pre-eclampsia, incompetent cervix, intrauterine growth restriction and other serious cardiovascular, respiratory, or systemic disorders. Females with absolute contraindications to antenatal exercise are recommended to continue their usual activities of daily living but should not participate in more strenuous activities that increase heart rate above 142 bpm (Mottola et al., 2018). Relative contraindications to exercise include recurrent pregnancy loss, gestational hypertension and eating disorders. These individuals are recommended to discuss the advantages and disadvantages of intense PA with their obstetric care provider.

Interestingly, recent findings have shown that a number of medical conditions have been classified as contraindications based on expert opinion but there is minimal empirical evidence to demonstrate harm of exercise and benefit of activity restriction (Meah et al., 2020). This research identified instances previously classified as contraindications to exercise, for example twin pregnancies and gestational hypertension, that may indeed benefit from regular antenatal PA. However, evidence suggests that contraindications such as placental abruption, intrauterine growth restriction and severe pre-eclampsia are associated with strong potential of exercise to cause harm. These findings demonstrate a gap in the literature and a lack of evidence used to inform list of contraindications for antenatal exercise. As well as a lack of scientific evidence in exercise recommendations for pregnant females with said contraindications to exercise, there is a distinct absence of scientific evidence regarding exercise at higher intensities during pregnancy. Therefore, greater research is required to inform PA and exercise guidelines for pregnant females to facilitate the development of clear and safe advice for participation in these health-giving activities during pregnancy.

Despite guidelines recommending pregnant females to perform as much activity as their non-pregnant counterparts (150 minutes of moderate-intensity activity per week) (Chief Medical Officers, 2019), as well as the aforementioned benefits observed in those performing antenatal PA, it has been reported that only 23-29% of pregnant females in the USA are meeting the guidelines (Hesketh and Evenson, 2016). However, recent data in the UK regarding the prevalence of pregnant females meeting the recommended PA guidelines is lacking. Females who were physically active prior to pregnancy have reported that their PA levels decreased during pregnancy (Coll et al., 2016). Decreases in PA levels are typically observed during pregnancy, owing to decreasing levels of overall and recreational activity (Borodulin et al., 2009, Borodulin et al., 2008, Clarke et al., 2005, Hinton and Olson, 2001, Pereira et al., 2007). Research has also found that although postpartum PA increases in comparison to pregnancy, females may not return to their earlier PA levels at postpartum due to lack of time, fatigue, or depressive symptoms (Borodulin et al., 2009). These changes in PA during pregnancy therefore suggest that pregnant females need educational tools from trustworthy sources promoting antenatal PA. These tools should consider the barriers to PA that pregnant and postpartum females face, such as lack of time and pregnancy symptoms, when promoting PA.

2.2.5.1. Metabolic Adaptations to Physical Activity in Pregnancy

It is well documented that PA during pregnancy decreases the risk of developing GDM (by 38%), pre-eclampsia (by 41%) and pregnancy-induced hypertension (by 39%) (Davenport et al., 2018b). Not only has research shown that habitual antenatal exercise may reduce the odds of developing GDM (Davenport et al., 2018b), but prenatal exercise after diagnosis of GDM is also recognised as a beneficial adjunct therapy to nutritional or medical management due to its glucose lowering effects (American Diabetes Association, 2015, Thompson et al., 2013). Results from a meta-analysis suggested that to achieve at least a 25% reduction in the odds of developing GDM, pre-eclampsia or gestational hypertension, pregnant females should accumulate 600 metabolic equivalent of task (MET)-minutes/week of moderate intensity exercise and the benefits would be attained when exercise is performed 3 days/week (Davenport et al., 2018b). Lower odds of developing GDM and hypertensive disorders of pregnancy with prenatal exercise have critical beneficial implications for the maternal and child long-term health.

In non-pregnant adults, an acute bout of exercise stimulates improved glucose uptake by translocation of glucose transporters onto the skeletal muscle cells surface (Richter and Hargreaves, 2013). Typically, circulating glucose concentrations in non-pregnant females decreases in the first 20 minutes of exercise before returning to pre-exercise values with longer duration exercise (Horowitz et al., 1997, Davenport et al., 2016). This is reported to be due to liver glycogen breakdown/release or glyconeogenesis (Horowitz et al., 1997). Yet, it is known that lower hepatic glycogen stores are available during pregnancy, which results in a continued decline in blood glucose levels (Davenport et al., 2016, Mottola and Christopher, 1991). Therefore, the blood-glucose lowering effects of exercise during pregnancy have been proposed to increase the risk of hypoglycaemic events (Seaquist et al., 2013). A systematic review and meta-analysis demonstrated that acute exercise reduced mean maternal blood glucose by 0.94 mmol/L and a reduction of 0.57 mmol/L was observed following acute exercise (Davenport et al., 2018c). These authors also found a dose-response relationship for glycaemic response to exercise, whereby a higher volume of exercise (intensity x duration) was associated with a larger decrease in blood glucose levels. Forty minutes of exercise, completed at 70% of pregnant females in their third trimester's $\dot{V}O_{2max}$, diminished glucose concentrations both during exercise and at 15 minutes post exercise compared to non-pregnant controls (Mottola et al., 2013). Acute exercise has also been demonstrated to reduce circulating insulin; however, insulin remains elevated in healthy pregnant females in comparison to healthy non-pregnant females during exercise, which may promote glucose transfer to the foetus (Mottola et al., 2013). Notably, Davenport and colleagues (2018) reported minimal incidence of maternal hypoglycaemia during acute antenatal exercise. Therefore, it appears that acute exercise beneficially impacts glucose during pregnancy without increasing the risk of hypoglycaemia.

Chronic exercise during pregnancy has been found to also decrease glucose levels. Davenport and colleagues (2018) demonstrated that fasting glucose levels of females randomised to an exercise-only intervention during their pregnancy were 0.48 mmol/L lower on average in comparison to non-exercising controls. Yet, sensitivity analysis revealed that this reduction in glucose levels was driven by females diagnosed with diabetes. Additionally, subgroup analyses identified significant reductions in fasting blood glucose values in females with GDM, females with overweight/obesity, and previously active females from before to chronic exercise. Therefore, chronic exercise does appear to beneficially impact maternal blood glucose. However, the clinical significance of these findings remains unknown, and the quality of evidence included in this systematic review was found to be 'very low' and 'low' due to risk of bias, inconsistency, and indirectness of the interventions being assessed. Future research is therefore warranted.

The mechanisms responsible for the impact of exercise on maternal glycaemic control remains debated. It has been proposed that the impact of acute exercise may be mediated by the increased hepatic glucose production and enhanced ß-cell function observed during pregnancy (Lain and Catalano, 2007). Moreover, the decrease evident in fasting blood glucose in response to chronic antenatal exercise may be related to enhanced GLUT-4 translocation to the skeletal muscle (Mottola and Artal, 2016). Improved glucose clearance and decreased hyperinsulinemia with acute and chronic exercise has been suggested to be a mechanism by which the risk of developing GDM can be reduced (Davenport et al., 2016). It is important, however, to note that timing of the last meal or snack the participant consumed prior to exercise may have a large impact on glycaemic response to exercise (Davenport et al., 2008).

There is also evidence that antenatal exercise improves the metabolic health of adult offspring, albeit evidence from rodent models (Stanford et al., 2017, Stanford et al., 2015, Carter et al., 2012, Laker et al., 2014, Raipuria et al., 2015). It has been suggested that maternal exercise before and during pregnancy improves glucose tolerance and insulin sensitivity in adult offspring (Harris et al., 2018). Rodent research has attempted to determine the time point at which maternal exercise is beneficial to confer positive effects on the metabolic health of adult offspring (Stanford et al., 2015). Authors divided female mice into four subgroups: trained (housed with running wheels before conception and during gestation), pre-pregnancy trained (housed with wheels preconception), gestation trained (housed with wheels during gestation), or sedentary (housed in static cages). They found that male offspring of sedentary dams had a worsening of glucose tolerance as they age, yet this effect was negated in the offspring if exercise was performed before and during gestation. Maternal exercise both before and during gestation improved glucose tolerance, as well as reducing fasting insulin and decreasing body fat percentage in male offspring compared to the other groups. These data indicate that maternal exercise during gestation improves glucose tolerance in male offspring, but maximal effects are evident if maternal exercise is performed both before and during gestation (Stanford et al., 2015, Carter et al., 2012, Sheldon et al., 2016). Future studies are required to determine whether these rodent observations investigating maternal exercise and offspring metabolic health are translatable to humans. Rodent model research is acknowledged as important in the bench to bedside model, but not wholly translational to human outcomes.

Given the known effects of exercise on maternal metabolic health, it is also important to consider the impact of habitual PA. Cross-sectional studies of accelerometery recorded PA in non-diabetic pregnancies have demonstrated that total PA demonstrates the strongest association with first-phase insulin secretion and estimated insulin sensitivity (Pomeroy et al., 2013, Gradmark et al., 2011). Similarly, studies examining habitual walking in diabetic (Hayashi et al., 2018) and non-diabetic (Hayashi et al., 2016) pregnant females reported lower glucose levels in females who recorded higher levels of walking. However, few published studies have utilised objective assessments of PA or glucose, meaning assessment of the relationship between PA and blood glucose levels is difficult. A recent study assessed the relationship of daytime PA and sleep disturbance, with accelerometery, and glycaemic control, with CGM, during pregnancy (Behravesh et al., 2021). Their data revealed that total movement improved glycaemic control in their non-diabetic pregnant participants (*n*=15). They reported that PA was strongly related with improved glycaemic control, whilst movement during sleeping periods tended to be associated with poorer glycaemic control. Food diaries, however, were not obtained throughout the study. Food consumption may coincide with activity bouts and, therefore, impact blood glucose variation (González-Rodríguez et al., 2019). Furthermore, preliminary results have shown that antenatal PA may decrease maternal metabolic markers during pregnancy. Studies have found that PA is significantly associated with lower triglyceride levels during pregnancy (Schreuder et al., 2011, Bo et al., 2014). Data from the OMEGA study in 925 healthy pregnant females at 13 weeks' gestation found that total cholesterol and triglycerides were inversely related to PA (Butler et al., 2004), therefore, suggesting that PA could improve lipid profile during pregnancy or females with better lipid profiles are more physically active compared to those with poorer profiles. Though, wide variability in study design, methods of assessing PA, the timing of metabolic marker assessments, and participant populations make results difficult to compare. Therefore, further research regarding the relationship between objective PA and metabolic health assessments in non-diabetic pregnant females across gestational age is necessary.

2.2.5.2. Mental Wellbeing, Physical Activity and Pregnancy

There is substantial evidence in the literature demonstrating PA as an effective strategy to also improve wellbeing in pregnancy. Previous studies have shown that reduced exercise levels during pregnancy are a key determinant of lower perceived quality of life (Mourady et al., 2017). A systematic review found mixed results when investigating the impact of aerobic exercise, resistance exercise, combined exercise, and yoga or PA on pregnant female's quality of life (Liu et al., 2019). Though, overall, the review provided evidence that prenatal PA is a viable, acceptable, and effective intervention for increasing female's quality of life during pregnancy. Exercise-only interventions during pregnancy have been associated with a reduction in the severity of prenatal depressive symptoms (standardised mean difference: -0.39 AU) (Davenport et al., 2018a). Davenport et al. (2018) reported that to achieve a moderate effect size in the reduction in the severity of prenatal depression symptoms, pregnant females must accumulate at least 644 MET-min/week of moderate-to-vigorous intensity exercise. They also found a dose-dependent association of this benefit, whereby a greater volume of exercise was associated with a greater reduction in the severity of prenatal depressive symptoms. Furthermore, authors found a 67% reduction in the odds of developing prenatal depression with exercise-only interventions. Yet, it has been reported that prenatal exercise does not reduce the symptoms or diagnosis occurrence of postnatal depression (Davenport et al., 2018a).

Sheffield and Woods-Giscombè (2016) systematically reviewed 13 studies examining the effects of yoga practice during pregnancy on prenatal symptoms of anxiety and depression. Of the five studies that examined anxiety symptomology, all studies reported significant improvements in state/trait anxiety inventory scores following a yoga intervention. Within these five studies, there were vast differences amongst interventions. All studies conducted yoga facilitated by a yoga teacher. Yet, in one study, a yoga teacher was utilised for 4 weeks then participants continued practices at home for 1-hour per day, though remained effective in reducing state/state anxiety inventory scores by 15.65% following the intervention compared to baseline. Moreover, longer intervention durations (>7 weeks) recorded more significant reductions in state/trait anxiety inventory scores (Field et al., 2013b, Field et al., 2013a, Field et al., 2012, Satyapriya et al., 2013) compared to the 7-week intervention conducted by Beddoe and colleagues (Beddoe et al., 2009). A number of studies offered participant incentives (i.e. $20 for each session attended), which likely influenced adherence to the interventions (Field et al., 2013b, Field et al., 2013a, Field et al., 2012). Yet, no studies recorded adherence. Ultimately, these findings suggest that yoga may be an effective strategy to reduce anxiety symptoms in pregnant females.

Findings from a systematic review by Kolomańska, Zarawski and Mazur-Bialy (2019) (Kołomańska et al., 2019) suggest that even a small amount of PA, for example one session of walking, yoga or swimming per week, during pregnancy may reduce the severity of depressive symptoms, as well as the occurrence of depression. In a large cross-sectional study (*n*=19842) including both males and females in the general population, Hamer and colleagues (2009) (Hamer et al., 2009) found that all types of PA (sports, walking and domestic activities) were associated with reduced odds of psychological distress. Despite the benefits of PA on depressive symptoms, some studies indicate that this association varied dependent on PA domain. Low-intensity exercises, such as regular walking, carried out during pregnancy has been reported to significantly reduce the symptoms of depression, for example low mood, in pregnant females (Petrovic et al., 2016, Taniguchi and Sato, 2016). Moreover, research investigating the influence of supervised training on depressive disorders shows that aerobic exercise performed at least 3x per week for 60 minutes in pregnant females significantly reduced the symptoms of depression (Vargas-Terrones et al., 2019, Robledo-Colonia et al., 2012, El-Rafie et al., 2016, Perales et al., 2015). Furthermore, studies have observed that PA 1-2x per week may also be beneficial in reducing the frequency and severity of depressive symptoms in pregnancy (Gjestland et al., 2013). These benefits of PA have been found not only in pregnancy, but also at early and late puerperium (Vargas-Terrones et al., 2019). Therefore, education of pregnant females about a healthy lifestyle that includes even low levels of PA during pregnancy appears paramount to improve overall quality of life in this population.

The mechanisms responsible for the increased quality of life scores for females who perform antenatal exercise remain unknown. It has been suggested that a perceived improvement in external appearance may influence female’s physical self-esteem and, therefore, quality of life (Rauff and Downs, 2011). Alternatively, exercise may counteract the dysregulation of biochemical and neurophysical function observed with depression by increasing norepinephrine, serotonin and dopamine levels (Davenport et al., 2018a). Though, further research regarding these mechanisms is required. Furthermore, a greater number of studies should aim to investigate the effects of exercise on improving maternal wellbeing in the first trimester and throughout pregnancy as most studies to date have focused on the effects of exercise during the second and third trimesters (Krzepota et al., 2018).

2.2.5.3. Perceptions of Physical Activity During Pregnancy

Despite the known benefits on antenatal PA for both mother and child, previous studies, carried out in different countries, observed low PA levels during pregnancy. Only 23-29% of pregnant females in the USA reported meeting 150 minutes of moderate-intensity activity (Hesketh and Evenson, 2016), whilst only one-fifth of pregnant females in Ireland met this target and over 10% reported zero PA (Walsh et al., 2011). Therefore, understanding of pregnant female's perceptions of antenatal PA is critical to increase participation and, consequently achieve the known physical and mental benefits.

Historically, females were advised to reduce activity levels during pregnancy and avoid strenuous exertion to minimise imposing a threat to their foetus (Hammer et al., 2000). Despite there only being few important precautions when exercising during pregnancy according to international guidelines (Pedersen and Andersen, 2011, Committee on Obstetric Practice, 2002, Davies et al., 2003, Mottola et al., 2018), quantitative studies have previously suggested a correlation between female's perceptions of risk of harm to their baby and a decrease in PA (Hanghøj, 2013, Clarke and Gross, 2004, Doran and O'Brien, 2007, Duncombe et al., 2009, Hegaard et al., 2010). Important precautions for exercising during pregnancy include avoiding activities with a high risk for trauma, such as collision or falling, as well as avoiding exercise in very hot or humid environments (Mottola et al., 2018). A study conducted in Australia in 158 pregnant females explored women's beliefs about the safety of antenatal PA and found that increased safety concerns negatively predicted the amount and intensity of exercise conducted (Duncombe et al., 2009). A number of studies have reported that previous bodily experiences, including miscarriages and fertility treatment, were perceived as a barrier to antenatal PA by pregnant females (Duncombe et al., 2009, Hegaard et al., 2010, Hanghøj, 2013, Evenson et al., 2009, Cioffi et al., 2010). Yet, studies have identified that relatives, partners and friends play an essential role in pregnant female's perception of risk and strongly influence their PA behaviours (Hanghøj, 2013, Clarke and Gross, 2004, Marquez et al., 2009, Downs and Hausenblas, 2004), whilst another study found that a lack of partner support could be associated with fear (Melender and Lauri, 2002). In accordance, health care professionals (HCPs) may consider providing additional reassurance regarding antenatal PA for females who have had a negative experience in pregnancy and be aware that female's relatives and friends play a crucial role in female's perceptions of risk.

Pregnant females have previously expressed frustration because they felt that they had not received specific guidance or education about the appropriate types, duration, or frequency of exercise to safely perform during pregnancy (Krans and Chang, 2011). An analysis of enablers and barriers to PA in overweight and obese pregnant females (Flannery et al., 2018) found the most commonly reported barrier to PA during pregnancy was knowledge about exercise. This finding was reflected in a qualitative study conducted in the USA, where pregnant females mentioned a lack of advice regarding PA (Evenson et al., 2009). Antenatal HCPs, namely midwives, are the key sources of information for pregnant females in the UK. It has been suggested that midwives' knowledge of the National Institute for Health and Care Excellence (NICE) PA in pregnancy guidelines is limited in the UK (Hopkinson et al., 2018). A UK study reported that health professionals considered verbal advice offered to females on lifestyle as inconsistent and unsupported by written information (Olander et al., 2011). Typically, midwives feel that they are restricted on time and resources to provide high quality advice to pregnant females about exercise (De Vivo and Mills, 2019). Additionally, lack of training, knowledge, confidence, and perception of vulnerability were identified as barriers to effective PA promotion by midwives (De Vivo and Mills, 2019). This lack of information about PA could have a detrimental impact on the motivation of pregnant females (Brown et al., 2013). By ensuring midwives and other HCPs have appropriate knowledge, skills, and opportunity to discuss PA with pregnant females, they may in turn be more motivated to perform PA during pregnancy.

A recent systematic review identifying predictors of physical inactivity among pregnant females explains that pre-pregnancy exercise status, sociodemographic, socioeconomic, lifestyle and health-related factors all contribute to activity levels amongst pregnant females (Yusof et al., 2020). Yusof and colleagues identified that pregnancy symptoms such as nausea, fatigue and pelvic girdle pain can prevent females from being active. This is consistent with previous literature, whereby feeling tired or a lack of energy are commonly cited reasons for inactivity (Evenson et al., 2009, Downs and Hausenblas, 2004, Leiferman et al., 2011, Duncombe et al., 2009). These barriers can change with stage of pregnancy (fatigue and nausea in early pregnancy and changes in size and shape later in pregnancy), therefore interventions aimed at increasing antenatal PA participation require flexibility to accommodate physical changes during pregnancy. These adaptations may include transitioning from land-based to water-based PA as pregnancy progresses. Whilst tiredness, work and a lack of time were significant reasons for all pregnant females to not be physically active, females with overweight and obesity reported that tiredness was more often a barrier for being active compared with normal weight and underweight females (Bauer et al., 2018). A study investigating barriers to engagement in antenatal PA according to BMI classification in German pregnant females found that fun, fitness, and well-being were the main reasons for exercising in females who were underweight or normal weight. Conversely, females who were overweight or obese reported that fitness and fat burning were the main reasons for them to be active (Bauer et al., 2018). Moreover, for females from low-income areas, accessibility, and affordability to a safe place for PA are key to enable antenatal PA participation (Krans and Chang, 2011). Therefore, tailored advice based on differences in motivational factors and barriers to participation may improve PA levels during pregnancy. Pregnancy-specific exercise groups that are time-efficient could be paired with antenatal visits and conducted by HCPs with knowledge of exercise, for example Physiotherapists, to offer reassurance and reduce barriers. Interventions should be fun and enjoyable to initiate and maintain behaviour change (Bozionelos and Bennett, 1999).

2.3. Impacts of the COVID-19 Pandemic for Pregnant Females

COVID-19 is a potentially severe acute respiratory infection, caused by the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The first cases of COVID-19 were detected in the city of Wuhan, China, during December 2019 and the virus was thereafter declared a pandemic by the World Health Organisation (WHO). To reduce transmission of COVID-19, the UK government enforced several measures. These measures included nationwide school closures, banning of public events, self-isolation for symptomatic individuals, closure of businesses, educational and public institutions, and stay-at-home orders aside from essential tasks and exercise (Institute for Government, 2021) (Figure 2.3).

It is known that some groups may be more vulnerable than others in experiencing severe COVID-19. Fragile populations, such as the elderly, pregnant females, or patients who are immunosuppressed or present multiple comorbidities, are more predisposed to experience severe symptoms of COVID-19 (Chen et al., 2020). Diabetes, hypertension, and CVD were common comorbidities observed amongst patients with COVID-19 requiring hospitalisation (Chen et al., 2020). The incidence and/or severity of these comorbidities have been found to be improved by PA. Greater PA levels are associated with reduced overall cardiovascular risks (Hegde and Solomon, 2015). PA has also been demonstrated to possess beneficial effects on metabolic syndrome and insulin sensitivity (Ahmed et al., 2012). Therefore, active individuals may have fewer and/or less severe comorbidities compared to sedentary individuals and accordingly be at a lesser risk of experiencing severe COVID-19.

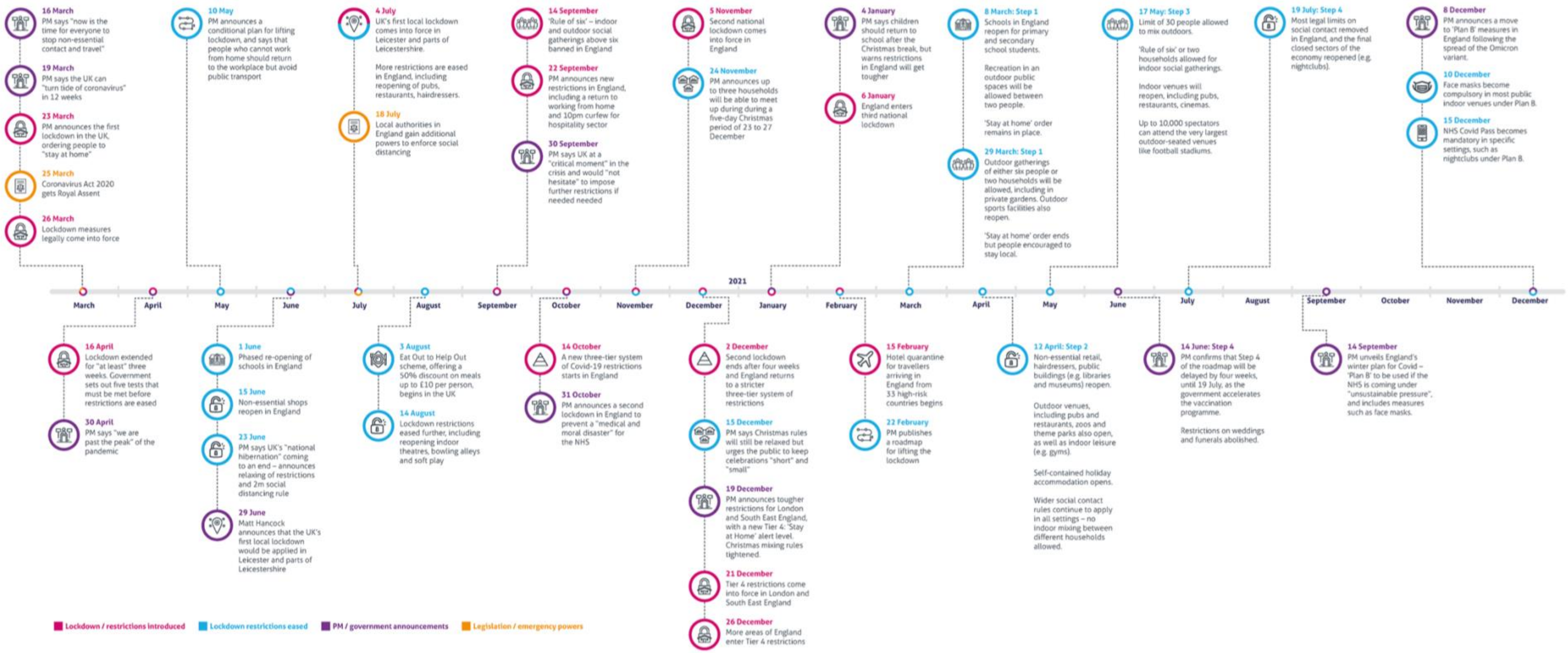

Figure 2.4 Timeline of UK Government COVID-19 measures, March 2020 to December 2021 (Institute for Government, 2021).

2.3.1. Impacts of COVID-19 on Mental Wellbeing During Pregnancy

Nationwide lockdowns, disruption of health-care services and fear of attending health-care facilities introduced significant challenges for the wellbeing of pregnant females and their babies (Roberton et al., 2020). Pregnant females were identified as a vulnerable group to COVID-19 (Di Mascio et al., 2020) and therefore were advised to take additional precautions, such as stay-at-home ('shield') in the third trimester. Additionally significant alterations were made to maternity care provision, for example staff and equipment was diverted to the provision of acute medical care, reducing the ability to screen for conditions such as GDM (Riley et al., 2020). Restrictions to maternity care also included a number of appointments being delivered remotely to reduce transmission risk, family member and partner presence being limited at appointments, and cancelled pre-birth courses. Studies indicate that prevalence of anxiety and depressive symptoms during pregnancy have increased during COVID-19 (Farrell et al., 2020, Lebel et al., 2020, Saccone et al., 2020, Davenport et al., 2020). Research conducted in Canada in 1987 pregnant females found elevated symptoms (above cut-off scores) of depression (37%) and anxiety (59%) were higher than expected based on previous pre-COVID-19 cohort studies assessing symptoms in pregnant females with similar demographics (Lebel et al., 2020). They suggested that these symptoms may be a direct consequence of the COVID-19 pandemic, as COVID-19-related worries were associated with higher symptoms. Moreover, pregnant females who are experiencing high stress during the COVID-19 pandemic are at risk of poorer perinatal outcomes (Preis et al., 2021). A systematic review investigating the effects of the COVID-19 pandemic on maternal and perinatal outcomes found increased maternal mortality and stillbirth, maternal stress, and ruptured ectopic pregnancies during the pandemic compared with before the pandemic (Chmielewska et al., 2021). The authors suggest that this increase in adverse pregnancy outcomes may be linked to reduced access to care.

Notably, these are emerging findings, and it is thought that the true extent of implications is not yet known.

Although maternal anxiety has been consistently shown to be increased during the pandemic, HCPs have reported reduced attendance for routine and unscheduled pregnancy care (Khalil et al., 2021, Dell'Utri et al., 2020, Chmielewska et al., 2021, Gu et al., 2020, Jardine et al., 2021). These reductions in attendance may be driven by concern about the risk of acquiring COVID-19 in health-care settings, government advice to stay at home, or reduced public transport and childcare access during lockdowns (Biviá-Roig et al., 2020, Goyal et al., 2021). Along with changes to healthcare, wider societal changes are also echoed in observed changes in maternal health. Intimate-partner violence has increased during the pandemic (Bradley et al., 2020) and has been highlighted as a contributor to increased maternal mortality (Knight et al., 2020). Additionally, females have been disproportionately more likely to become unemployed and provide childcare due to school closures (Gewin, 2020). These findings, therefore, likely have negative impacts on maternal mental wellbeing. A longitudinal investigation to determine the long-term consequences of maternal wellbeing on long-term implications as well as infant outcomes is warranted.

A study in the USA reported that both pregnant females and nurses highlighted several changes to healthcare in response to COVID-19 that adversely affected their care or ability to provide care (Altman et al., 2021). Moreover, among females who gave birth in Italy during the pandemic, 75% of 739 females conveyed being afraid of giving birth during COVID-19 (Stampini et al., 2021). Yet, 87% of patients felt that the overall healthcare experience was as expected or better than expected. These results suggest that apprehensions about giving birth during the COVID-19 pandemic may not be due to negative healthcare experience. Furthermore, nurses in the USA perceived the policy roll-out related to the pandemic as inadequate, which led to a mistrust in management and administration (Altman et al., 2021). Ultimately, many nurses in the study conducted by Altman *et al.* (2021) felt unsafe and unsupported, which had a direct effect on patient care experiences. These studies indicate that the COVID-19 pandemic had significant impacts at the systemic level. Increasing mental health assessment, support, and services for both pregnant females and HCPs during the pandemic is warranted. Additionally, increasing transparency, communication and reassurance around policy changes may help to reduce feelings of distress in both HCPs and patients.

As above, findings reported an association between increased anxiety and depression symptoms with COVID-19-related worries (Lebel et al., 2020). Yet, it is important to acknowledge that expectations are key determinants for maternal mental health (Preis et al., 2019) and many pregnant females will also not have been able to experience pregnancy as they'd initially expected. Due to COVID-19 restrictions, females may have limited opportunities to socialise. Better perceived social support is significantly associated with decreased symptoms of depression and anxiety (Cohen, 2004). Previous research also indicates decreased antenatal and postnatal anxiety and depression among females with higher levels of social support (Akiki et al., 2016, Friedman et al., 2020). Therefore, despite pregnant females experiencing substantially elevated anxiety and depression symptoms during the COVID-19 pandemic, social support remains a protective factor. In accordance with the social distancing advice and limiting hospital visitations, psychological hotlines and online counselling may be useful strategies to manage mental wellbeing during pregnancy.

2.3.2. Impact of COVID-19 on Physical Activity During Pregnancy

Government restrictions in response to COVID-19 have reduced opportunities for exercise due to the closure of gyms and leisure facilities as well as less opportunities for active travel to work and school. Closure of schools and childcare facilities may have also reduced time available for parents to be physically active. Additionally, fewer, and shorter healthcare appointments may reduce opportunity for PA advice. PA during pregnancy has been associated with reduced depression and anxiety (Demissie et al., 2011, Lebel et al., 2020). In accordance, it is important that other credible sources of information and advice should be promoted during this time.

The Active Pregnancy Foundation survey completed by 445 pregnant and postnatal females found that 50% of participants were participating in less PA during lockdown in comparison to previously (Active Pregnancy Foundation, 2020). However, both the Active Pregnancy Foundation and Sport England data show that approximately a third of their participants reported higher levels of PA during lockdown than in the weeks prior (Active Pregnancy Foundation, 2020, Sport England, 2020). Moreover, 88% of females who participated in the Active Pregnancy Foundation survey (Active Pregnancy Foundation, 2020) indicated that PA helped their mental health. Similarly, a large survey conducted by Davenport *et al*. (Davenport et al., 2020) reported that pregnant and postnatal females who met PA guidelines (of 150 minutes of moderate intensity PA per week) during the pandemic had lower levels of depression and anxiety. This suggests that there is a protective effect of PA on mental wellbeing and is likely an important tool to help pregnant females during the COVID-19 pandemic. Development of comprehensive and appropriate promotional strategies for antenatal exercise for during the COVID-19 pandemic requires attention.

2.4. Remote Research

2.4.1. Feasibility of Remote Interventions

Remote access to clinical trials presents many potential benefits for some minority groups traditionally underrepresented in research, for example people of colour, those living in poverty, social housing, and food insecurity and, additionally, those living in rural areas (Noonan and Simmons, 2021). The decrease or elimination of research facility visits may also expand representation of those with limited resources, such as time, travel, and money. Therefore, the development of remote studies could decrease clinical trial disparities and promote health equity throughout the country. Despite these benefits of remote data collection for research, little is known about the feasibility and acceptability of conducting remote studies. Therefore, the potential impact of findings from remote studies remains undetermined. Investigation of the feasibility and acceptability of remote data collection is necessary to understand the effectiveness of this study design.

Previous literature has suggested that supervised exercise delivered by an appropriately trained exercise specialist promotes greater adherence in a variety of populations (Vancampfort et al., 2016, Stubbs et al., 2016). Yet, supervised exercise interventions may be a considerable burden for the researcher and participant due to time commitments and the requirement to travel. Research studies that include unsupervised exercise with or without counselling in previously sedentary individuals indicate poor adherence rates to the recommended exercise (Jung et al., 2020, Hesketh et al., 2021, Roy et al., 2018). These interventions have also reported high participant drop-out, ranging from 24-49% (Jung et al., 2020, Hesketh et al., 2021, Roy et al., 2018), along with missing data of key physiological or clinical outcomes, which pose serious threats to both internal and external validity. The development of research study designs that can increase participant retention and minimise data loss are therefore required. Home-based exercise interventions may reduce some barriers to supervised programmes as individuals may not be required to travel or plan their day around the session. Nevertheless, research has shown that home-based interventions create additional barriers for participants that include a lack of support and feedback from exercise specialists (Bachmann et al., 2018).

2.4.2. Use of Mobile Health Technologies for Exercise Interventions

Advances in mHealth technologies could provide an opportunity to facilitate feedback between the researcher and participant to increase support and feedback (Hawkins et al., 2017). Recently, there has been an increase in the employment of mHealth technologies, such as wearable smartwatches and mobile applications, as an intervention support modality. This may be because technology devices are typically portable, allow for continual self-monitoring, they are cost-effective, convenient, and give the user a sense of control (Thomas and Bond, 2014, Khaylis et al., 2010, Bacigalupo et al., 2013). There are many mHealth technologies available, such as applications on smartphones and wearable devices that promote and support self-monitoring of fitness and wellbeing, providing insights about activity, dietary intake, and weight. In 2019, fitness trackers and smartwatches (e.g. Fitbit, Apple watch, Garmin) were reported as the number one fitness trend, with 19% of Americans owning at least one (Statista, 2021). Many mHealth applications utilise social media or other online platforms to share data with peers. mHealth technologies are increasingly being used in PA interventions as they can be used at any time and in any environment, permitting objective and reliable data collection (Kooiman et al., 2015, Eapen and Peterson, 2015). The use of mHealth technologies to promote PA has been deemed effective in multiple populations, for example individuals who are pregnant (Chan and Chen, 2019, Overdijkink et al., 2018), those with cardiometabolic conditions (Hodkinson et al., 2021) and older adults (King et al., 2016). Five components have been recommended to be incorporated in technology-based interventions: self-monitoring, counsellor feedback, social support, structure and principles of behaviour change, and an individually tailored program (Khaylis et al., 2010). Although there are clear benefits of mHealth interventions, such as cost-effectiveness, the ability to support unsupervised exercise, and measurement of continual data, may come with additional barriers. Costs of mHealth technologies are reducing, however remain unaffordable for lower socio-economic groups, and therefore potentially widening health inequalities.

A systematic review and meta-analysis conducted in 2019 in healthy individuals (Brickwood et al., 2019) reported a significant improvement in all measures of PA participation when utilising a consumer-based wearable activity tracker, in comparison to control groups. The authors suggested that interventions that incorporate multifaceted approaches appeared to have a greater effect on PA participation when compared with control groups. These multifaceted approaches included consumer-based wearable activity trackers as well as telephone counselling, financial incentives, or group-based education (Finkelstein et al., 2016, Shin et al., 2017, Van Hoye et al., 2015). Similarly, a recent systematic review and meta-analysis among adults with cardiometabolic conditions (Hodkinson et al., 2021) found that interventions using activity trackers were associated with significant improvements in PA compared to those who received usual care. Though, again, interventions that combined the use of activity trackers with additional components had the strongest associations with PA improvement. A 4-week intervention study in healthy adults found that those with an activity tracker having a weekly meeting with a coach increased PA levels whilst those using just an activity tracker alone did not significantly increase their PA levels (Van Hoye et al., 2015). Yet, the high baseline activity level of the sample may have limited significant improvements in PA. The heterogeneity in activity monitoring systems and reporting of PA makes it difficult to compare PA changes across studies, and thus draw meaningful conclusions. Though research, overall, provides encouraging evidence regarding the effectiveness of mHealth technologies for PA promotion in multiple populations. Despite the positive findings, availability of long-term follow-up data is limited (Brickwood et al., 2019). Additionally, the effectiveness of mHealth technology to increase adherence to and uptake of exercise, rather than PA alone, has received less attention. Furthermore, mHealth technology interventions have seen improvements in body weight (Pellegrini et al., 2012, Reijonsaari et al., 2012, Thompson et al., 2014, Shuger et al., 2011), BMI (Pellegrini et al., 2012, Shuger et al., 2011), and blood glucose levels (Hodkinson et al., 2021). Yet, other studies have reported no improvements in secondary health outcomes such as blood pressure, cholesterol levels, weight, and BMI, associated with the intervention (Hodkinson et al., 2021). Therefore, whether the mHealth technologies used to promote PA can improve secondary health outcomes across longer time periods deserves further systematic investigation.

CHAPTER 3: GENERAL METHODS

Several measurements undertaken in *Chapters 4 and 5* are utilised in both studies. This *General Methods* Chapter describes physiological measurement techniques, and data analysis methods. Specific research designs, protocols and statistics for each study are outlined within the respective chapters.

3.1. Data Collection

At least 3 days prior to the proposed testing date, participants were sent all the necessary testing resources (direct to participants preferred address), including detailed instructions (Appendix 1) for use via ParcelForce. The kit included a blood pressure monitor, CGM, measuring tape, scales, PA monitors and a diet diary. Participants had a phone/video call from the research team to discuss the testing protocol and answer any question that the participants had. On the day of testing, a member of the research team was available via phone/video call to provide support where required.

Testing was scheduled on a morning between 6am and 10am. Participants were asked to abstain from any vigorous intensity exercise for 24 hours, alcohol for 12 hours and any food/caffeine/stimulants for at least 6 hours prior to completing the testing procedure. Participants were asked to drink a glass of water immediately before performing the testing protocol.

3.1.1. Anthropometrics

Height and weight were measured using a tape measure (SECA 201, Germany) and digital scales (Salter, China), respectively. Participants were asked to measure their waist circumference by wrapping a tape measure (SECA 201, Germany) around their waist at the level of the umbilicus whilst breathing out gently. This was repeated in triplicate.

Participants measured body mass using scales they already own. If participants did not have scales, they were provided with these via post (Salter, UK). Height was measured using the same measuring tape (SECA 201). BMI was calculated as body mass in kilograms divided by height in metres squared (kg/m^2). Participants rested in a seated position for 10 minutes before measuring their blood pressure. Blood pressure was measured in triplicate, using an automated blood pressure monitor validated by the British and Irish Hypertension Society (UK, Salter BPA-9200-GB; CA, Bios BD215), leaving 1 minute between successive measurements.

3.1.2. Physical Activity Monitoring

PA was monitored using a wrist-worn tri-axial accelerometer (GT9X, ActiGraph, Pensacola, FL, USA). Participants wore the accelerometer on their non-dominant wrist for seven consecutive days. Participants were instructed to remove the device for sleeping (if preferred) and water-based activities. Accelerometers were initialised using ActiLife software (version 6.13.4). The accelerometer was pre-set to record at 30Hz to account for transit in the post, while optimising the battery life of the device. Data were downloaded using ActiLife version 6.13.4 (ActiGraph, Pensacola, FL, USA), and saved in raw csv format for signal processing.

Figure 3.1 ActiGraph GT9X Link

3.1.3. Continuous Glucose Monitoring

A CGM (Freestyle Libre Pro, Abbott Diabetes Care, Alameda, California, USA) was placed subcutaneously at the tricep of one arm to measure interstitial fluid glucose levels. This monitor was worn simultaneously with the PA and sedentary behaviour monitors for 7 consecutive days. Objective monitoring devices were worn for 7 days rather than 14, as recommended in the current American Diabetes Association (ADA) guidelines (Battelino et al., 2019, Danne et al., 2017) to reduce participant burden. Participants were instructed to scan the sensor at the beginning and end of the monitoring period with a Freestyle Libre Reader. The CGM device was blinded so that participants were not influenced to alter diet, PA, or general lifestyle.

Figure 3.2 Freestyle Libre Pro continuous glucose sensor (left) and monitor (right).

3.1.4. Capillary Blood Sampling

Participants collected a 500µl capillary blood sample from a finger prick, using a commercial blood collection kit, administered via Royal Devon and Exeter NHS Foundation Trust (MonitorMyHealth.org.uk). Prior to collection, participants were instructed to wash their hands with soap and warm water for 2 minutes, ensuring their hands were warm. Participants cleaned their chosen finger with the alcohol prep pad and allowed to air dry. The first drop of blood was washed away with gauze and participants then massaged their finger to fill the tube to the correct level (500µl). Blood collection kit preparation and sample analysis was performed by the Exeter Clinical Laboratory, based at the Royal Devon and Exeter National Health Service (NHS) Foundation Trust. Samples were sent directly to the Exeter Clinical Laboratory for analysis, via Royal Mail.

3.2. Data Analysis

3.2.1. Physical Activity Monitoring

The open-source R software package, GGIR beta v1.6-1, was used to analyse accelerometery data. GGIR converted raw triaxial acceleration signals into one omnidirectional measure of acceleration to signal vector magnitude (SVM) values (Van Hees et al., 2014). SVM was then processed to remove the gravitational component and noise from the raw signal to Euclidean Norm Minus One (ENMO). Parts 1 and 2 of the GGIR software package were utilised in this study. During part 1 (g.part1), metrics for sensor wear detection, PA and sleep analysis are extracted from the raw data (Migueles et al., 2019). Part 2 (g.part2) identifies any unreliable signal sections and replaces the sections with imputed values (Migueles et al., 2019). A descriptive analysis of the output is performed via g.analyse and summarises it per measurement, per day and per segments of each day (Migueles et al., 2019). Part 2 also provided a visual report output with timestamped ENMO values every 5 seconds of recording.

Accelerometer wear time inclusion criteria were at least 10 hours, for a minimum of 4 days (including at least 1 weekend day). This has been demonstrated to be an appropriate period of time to reliably estimate PA (Trost et al., Atkin et al., 2012; Aadland et al., 2013; Green et al., 2014). Non-wear time was defined as ≥ 60 minutes of consecutive zeros (Tudor-Lock et al., 2012; van Hees et al., 2013) and was determined based on the SD and value range of accelerations at each axis, calculated for 60-min windows with a 15-min sliding window (van Hees et al.,2013). Timepoints with SD values < 13mg, or value range < 50mg, for at least 2 out of 3 axes, were classified as non-wear (van Hees et al., 2013). Classification of activity intensity was performed using adult-specific cut-points (Hildebrand et al., 2014; Hildebrand et al., 2017). Inactive time was defined as time accumulated below 45 mg, light PA was defined as ≥ 46 and < 101 mg, moderate PA was defined as ≥ 102 and <428 mg, and vigorous PA was defined as ≥ 429 mg.

3.2.2. Continuous Glucose Monitoring

Metrics of glycaemia were assessed in line with the ADA guidelines (Danne et al., 2017, Battelino et al., 2019); mean glucose (mmol/L), coefficient of variation (CV) (%), % time below range (TBR), % time above range (TAR), % time in range (TIR). Values for ranges are reported in appropriate studies due to differing target ranges in different populations. Metrics of glycaemia were assessed and reported for the full 7-day measurement period (24 hours per day).

CHAPTER 4: MOBILE HEALTH BIOMETRICS TO ENHANCE EXERCISE AND PHYSICAL ACTIVITY ADHERENCE AT LJMU (MOTIVATE_LJMU): A MIXED METHODS MODEL TO ASSESS FEASIBILITY OF HOME-BASED TESTING

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CHAPTER 5: PHYSICAL ACTIVITY AND GLUCOSE CONTROL ACROSS THE PERINATAL PERIOD: DOES A RELATIONSHIP EXIST?

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CHAPTER 6: PERCEPTIONS OF ANTENATAL EXERCISE IN PREGNANT FEMALES AND THE IMPACT OF COVID-19

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CHAPTER 7: SYNTHESIS OF FINDINGS

7.1. Aims and Objectives

The overarching aim of this body of work was to investigate the acceptability and feasibility of remote data collection to explore PA and glucose control across the perinatal period. In addition, thematic analysis of semi-structured interviews aimed to identify pregnant female's perceived barriers to antenatal exercise and the impact of the COVID-19 pandemic on the pregnancy experience.

This synthesis first conveys *reflections from the researcher*, which outline the unique journey taken to produce this body of work. This synthesis then goes onto briefly summarise the findings of the three research studies, presented within *Chapters 4-6* of this thesis. It then draws on the collective findings of the three studies to consider the practical application of such findings and recommendations for future research.

7.2. Reflections

In this section, the researcher will refer to themselves in the first person to discuss reflections from their PhD programme.

My PhD journey has been incredibly rewarding and valuable. I have gained a multitude of skills and experiences that will contribute to my evolution as a researcher. These skills include co-production of research studies, lab-based physiological testing techniques, remote testing, as well as qualitative data collection in the form of interviews and the processing/analyses of all aforementioned data sets. The qualitative study described in this thesis is the first qualitative study I have conducted. I therefore undertook significant training to conduct robust and transparent qualitative research methods. Despite initial trepidation, qualitative research has been an enjoyable feature of my PhD. Another first, and unplanned element, of my PhD studies was coordinating remote research trials. Conducting each aspect of a research trial over a combination of social media (recruitment) and zoom/telephone calls (participant interaction including consent, data collection etc) was demanding and, at times, frustrating. Importantly, I have learned how to pre-empt challenges where possible and have further developed my communication skills to ensure that the participant's full understanding is achieved over a phone or video call. On reflection, and particularly after reviewing the literature in relation to this unique aspect of the trials, I identify this as a strength in our design and hope to incorporate this option in future research design to promote inclusion of underrepresented groups which will hopefully contribute to the important aspiration of bridging gaps in scientific literature.

Study design and data collection for *Chapter 4* was conducted as part of a research team, consisting of three academic staff, two post-doctoral researchers, two PhD candidates, including myself, and an MPhil student. Working as part of this team taught me that different people work effectively in different ways, and each have their own unique strengths, therefore, clear communication and compromise are required to operate as a successful and productive research team. Furthermore, when analysing data and drafting this chapter there were wider inputs to consider than just those of my supervisory team. Whilst this came with the obvious positive of more expert option to guide the evolution of this work; more expert opinion can also be difficult to navigate. This has helped me to appreciate the value of weighing up and fully understanding different perspectives before reaching my own, informed, decisions. Ultimately, this experience has advanced my ability to use my own initiative/lead autonomously and work as part of a team.

To ensure optimal data collection, as participants were conducting their own measurements at home, I created a series of instructional videos and booklets as supporting aid for the participants. This required short and effective communication to a range of individuals who were non-experts and in fact may not be familiar with any of the health assessments we were asking them to carry out. This task challenged my ability to communicate with non-specialist audiences and made me realise how essential this skill is in human research. Moreover, I have also received recognition for presenting to a lay audience during my PhD, as winner of School of Sport and Exercise Science Three Minute Thesis competition (2021), where I presented an 'elevator pitch' of my PhD thesis in just 3 minutes. This has amplified my passion for translating clinical and scientific findings to end users and my belief in my ability to do this.

As well as the many positive learning experiences and reflections, my PhD programme has not been without challenge. I enrolled on this PhD in January 2019 and, following study set up (sponsorship, ethical approval etc), began data collection for a longitudinal study exploring cardiovascular and metabolic health during pregnancy. In March 2020, face-to-face research was suspended indefinitely, resulting in the cancellation of several testing sessions and a halt to recruitment. Given that the participants I was recruiting were pregnant females, this resulted in the loss of data from several participants, as pregnancy cannot be paused to account for a global pandemic and resultantly this longitudinal study could not be completed. Initially, we had planned to resume the study (from scratch) but once it became clear that face to face research would not resume anytime soon, my supervisory team and I decided to design new studies that could be completed remotely in order to complete my PhD within the proposed timeline. Despite feeling overwhelmed and uncertain about completely changing the scope of my PhD at the time, I have learnt a wider variety of skills due to these changes and worked with a more diverse set of colleagues, for which I am grateful.

The hurdles faced during my PhD programme demanded adaptability and practical thinking. Being involved in the research design has also enhanced my understanding of the research process. Taken together, my experiences during my PhD have moulded me into a versatile mixed methods researcher.

7.3. Summary of Major Findings

Chapter 4 demonstrated that remote data collection is a feasible data collection technique. Moreover, home-based exercise interventions that incorporate individualised support and mHealth technology, were deemed effective to increase exercise intensity and improve health outcomes in sedentary individuals. The key components of the home-based exercise intervention included live visual and haptic feedback via mHealth technology with information regarding timing of intervals or HR zone as well as individualised exercise counselling consultations pre-intervention, and at regular intervals throughout the 12-week intervention period (week 4, and week 12).

Chapter 5 identified negligible changes in glucose variability during pregnancy trimesters, but a decrease in glucose variability at postpartum. The change in glucose variability at this timepoint may indicate that glucose variability is increased during pregnancy before returning to normal levels at postpartum, or that the postpartum period is a unique timepoint in female metabolic health. Although likely influenced by breast feeding, the postpartum period could provide physiological insight into how to enhance female metabolic health with ageing and poor lifestyle. Negligible changes in glucose variability were evident despite increases in objectively measured light PA across the perinatal period. Moreover, no relationship was evident between PA and glucose control during pregnancy or at postpartum. Though, higher levels of PA and/or structured exercise may be required to maintain metabolic health.

Chapter 6 highlighted access to credible information and better education is essential to antenatal exercise in pregnant females during the COVD-19 pandemic. Direct psychosocial support and clear, trustworthy information for pregnant females is essential. These findings should be used to inform development of future exercise and PA interventions strategies, inform guidelines, and educate healthcare practitioners.

7.4. General Discussion of Major Findings

The section that follows will discuss the major findings in this thesis under the themes of i) glucose control in pregnancy, ii) PA in pregnancy, iii) remote testing, iv) the impact of COVID-19 on maternal wellbeing.

7.4.1. Glucose Control in Pregnancy

Poor glucose metabolism leads to metabolic dysfunction, including T2DM (Nakrani et al., 2020). Variability in glucose levels may occur due to physiological dysfunction and changes in the circadian rhythm of endogenous hormones, nutrition, or PA (Wang et al., 2012). Although glucose variability is typical, variability is magnified in sedentary, overweight, or obese (but otherwise healthy) individuals (Salkind et al., 2014). Moreover, variability in glucose levels during pregnancy have been related to adverse foetus development (Law et al., 2015, Murphy, 2019, Kristensen et al., 2019), and at postpartum have been associated with impaired islet β cell function and therefore insulin resistance (Wang et al., 2015). PA is well evidenced as beneficial to overall health and, to that end, physical inactivity is known to increase the risk of developing T2DM and CVD (Chan et al., 2004). Moreover, PA in pregnancy has a beneficial effect on glucose control and has been associated with a reduced risk of GDM (Aune et al., 2016). In order to identify intra- and inter-day glycaemic excursions, CGM can be utilised as an effective measure of continuous real-time measurements of glucose levels (Yogev et al., 2004).

One of the novel aspects of this thesis was to examine glucose variability across the perinatal period in healthy individuals that disaggregated data by trimester and postpartum. Previous literature has examined glucose variability in pregnant females with type 1 diabetes (Kristensen et al., 2019, Murphy, 2019), or both type 1 and type 2 diabetes (Law et al., 2015), and reported an association between higher glucose variability and adverse birth outcomes (Kristensen et al., 2019, Murphy, 2019, Law et al., 2015). These data therefore demonstrate the potential importance of measuring glucose variability and the need for further research with a formation of healthy reference values across the perinatal period. *Chapter 5* observed no change in glucose variability occurred from T2 to T3, followed by a non-significant decrease in glucose variability postpartum. Given the study design, whereby data were disaggregated by trimester and therefore a wide range in weeks gestation within a trimester was evident, no change in variability from T2 to 3 may not be surprising. Differing sleep and eating schedules, as well as the potential addition of breastfeeding, may also influence glucose variability at this timepoint. Twenty-two participants in *Chapter 5* (81% of participants who answered the question) reported breastfeeding.(Gunderson et al., 2012) Moreover, breastfeeding has been shown to have a beneficial effect on mean fasting glucose, total area under the glucose tolerance curve, and mean 2-hour glucose levels in females with prior GDM (Kjos et al., 1993). Further research should assess changes in glucose variability from prepregnancy to postpartum with comparison to non-pregnant controls to understand whether glucose variability does in fact increase during healthy pregnancy and decrease at postpartum, or whether postpartum presents a unique timepoint that could provide useful information for long-term maternal health.

An additional novel element of this thesis was assessment of the relationship between PA and glucose control across the perinatal period, disaggregated by trimester and postpartum, using objective continuous assessment methods. Recently, research has observed a significant relationship between PA and glucose variability, whereby increased PA was associated with decreased glucose variability (Behravesh et al*.,* 2021). The prospective study by Behravesh and colleagues (2021) collected objective continuous data over 20 gestational weeks in 15 healthy pregnant females. However, as discussed in *Chapter 5*, authors did not disaggregate data by trimester despite previous research highlighting trimester-specific differences in maternal glucose excursions (Law et al., 2015). *Chapter 5* contradicted these findings and instead reported no relationship between PA and glucose variability across the perinatal period, disaggregated by trimester and postpartum. It is plausible that the differences observed between this thesis and research by Behravesh and colleagues (2021) may be dependent on differing glucose variability measurement methods (e.g. glucose rate of change and CV) or statistical analyses (incorporating all data points or averaged weekly data).

Another possible explanation for the lack of relationship between PA and glucose control observed in *Chapter 5* could be due to the low levels of PA recorded by participants. Cross-sectional studies utilising accelerometery data have previously demonstrated that total PA is strongly associated with first-phase insulin secretion and estimated insulin sensitivity in non-diabetic pregnant females (Pomeroy et al., 2013, Gradmark et al., 2011). Moreover, higher levels of habitual walking have been associated with reduced non-fasting glucose levels in pregnant females with (Hayashi et al., 2018) and without GDM (Hayashi et al., 2016). The low PA levels recorded in *Chapter* 5 may be attributed to barriers identified by pregnant females in *Chapter 6,* such as limited access to classes and facilities during the COVID-19 pandemic and lack of time. A greater range in participant's activity levels may yield different findings in *Chapter 5*. Furthermore, increases in PA intensity or volume may positively impact glucose control across the perinatal period. Additionally, night-time PA or sleep, which is known to possess a substantial influence on glucose metabolism (Byberg et al., 2012), were not measured in *Chapter 5*. Longer sleep duration has been associated with a 25% decreased risk of impaired glucose regulation, whilst greater sleep quality has been associated with increased insulin sensitivity (Byberg et al., 2012). Further studies in healthy populations, therefore, should acknowledge this important variable and, accordingly, monitor sleep and night-time PA to examine their impact on glucose homeostasis across the perinatal period.

7.4.2. Physical Activity in Pregnancy

In *Chapter 5*, an increase in light PA across the perinatal period was observed. These findings are supported by Hesketh and colleagues (2018) who measured PA at T2, T3, and 3-, 6-, 9-, and 12-months postpartum using wrist-worn accelerometers (ActiGraph GT3X+ with Troiano et al. (2008) cut-points). This increase observed in light PA, despite no detected change in MVPA, may reflect changes in activity type during the transition into parenthood (Borodulin et al., 2008). Nevertheless, low levels of PA were reported at all time-points measured in *Chapter 5*. Thematic analysis of semi-structured interviews in *Chapter 6* revealed perceived barriers to antenatal exercise in pregnant females. Findings demonstrated the importance of credible information and better education to encourage antenatal exercise. Females reported struggling to exercise during pregnancy due to experiencing pregnancy symptoms such as nausea, pelvic girdle pain and fatigue. Additionally, participants acknowledged that accessibility, whether that be to facilities or time, had a significant influence on their PA during pregnancy. These barriers were in line with previously reported barriers to antenatal exercise (Yusof et al., 2020) and may have contributed to the low levels of activity observed in *Chapter 5*. Taken together, *Chapter 6* findings suggest that interventions to increase PA in pregnant females should incorporate peer support and educational strategies. *Chapter 4* demonstrated the effectiveness of home-based exercise interventions, that incorporate individualised support and mHealth technology in sedentary individuals. Home-based exercise interventions that include peer support from credible sources, such as the newly established Clinical Exercise Physiologist professional title (Jones et al., 2021), may be a feasible strategy to increase PA in pregnant females and reduces several the previously discussed identified barriers, such as lack of facilities, time, and education.

Government restrictions to decrease transmission of COVID-19 included prohibiting non-essential travel and allowing only 1 hour of outdoor exercise per day. These restrictions reduced opportunities for exercise. Moreover, fewer, and shorter healthcare appointments for pregnant females could have reduced opportunity for PA advice. Despite the known, and previously discussed, benefits of antenatal PA, the Active Pregnant

Foundation survey found that 50% of participants were performing less PA during lockdown in comparison to before restrictions were imposed (Active Pregnancy Foundation, 2020). Findings from *Chapter 6* identified midwifery appointments as a significant opportunity to promote antenatal PA. Additionally, *Chapter 6* revealed that pregnant females felt they lacked sufficient time to exercise, which may have been exacerbated due to closure of schools and childcare facilities with government restrictions. These qualitative findings may therefore help contextualise low PA levels observed in *Chapter 5*. Moreover, the increase in light PA levels observed across the perinatal period in *Chapter 5*, may be in fact due to relaxation of government restrictions, subsequently aiding PA participation. Therefore, it is acknowledged that these data collected during this unique period may not be directly comparable to previous literature. Findings from *Chapter 6* suggest that midwifery appointments may be an effective opportunity to enhance awareness and understanding of PA guidelines. Yet, research has identified a limitation in training, knowledge, confidence, time, resources, and perceptions of vulnerability as barriers to effective PA promotion (De Vivo and Mills, 2019). Accordingly, HCP and midwifery education on antenatal PA and exercise should be considered a priority.

7.4.3. Remote Testing

Benefits of remote data collection could include wider accessibility for groups traditionally underrepresented in research by decreasing or altogether eliminating research facility visits. Yet, the feasibility and acceptability of remote data collection required investigation to understand the effectiveness of this study design. *Chapter 4* demonstrated that remote data collection is feasible and identified issues that may improve data capture (Table 7.1).

Feasibility was supported by the low percentage of missing data *Chapters 4* (16%) *and 5* (12%) and encouraging qualitative survey and interview data obtained in *Chapter 4*. Remote data collection also allowed greater access and inclusivity in those from a range of socioeconomic backgrounds in *Chapters 4, 5 and 6* as measured using IMD (3 ± 1 AU in all Chapters) and the range in distance from the research facility to participant homes (*Chapter 4:* 35.52 ± 74.27 miles; *Chapter 5:* 78.15 ± 94.15 miles; *Chapter 6:* 80.92 ± 92.68 miles drive). These promising findings in sedentary adults and pregnant females demonstrate the potential of an innovate research design, such as remote data collection, to promote health equity within research. However, common variables included within exercise intervention studies, such as $\dot{V}O_{2max}$ to measure CRF, are difficult to measure remotely. Several promising studies have investigated mHealth technology estimates of CRF; they have observed that smart watches provide consistent and unbiased, albeit overestimated, estimates of CRF, suggesting that this is appropriate for repeated measures designs to detect change (Freeberg et al., 2019, Klepin et al., 2019, Carrier et al., 2020). Nevertheless, further research to validate reliable CRF estimation using mHealth technologies for use within clinical research remains warranted. Moreover, data collection investigating the validity and reproducibility of remote data collection in comparison to laboratory data collection is underway in our laboratory.

Table 7.1. Evaluation of remote measurement techniques, identification of changes made to data collection, and the implications of these changes.

Issue identified in Chapter 4	Change in Chapter 5 methods	Implications of change
51% valid PA monitoring data collected at post-intervention	Use of participant diary to increase uptake and remind participants to wear monitor	Greater amount of valid PA monitoring data (86% at T2, 87% at T3, 86% at T4).

Missing lipid blood collection data (72% at post-intervention), primarily due to insufficient volume of sample or haemolysed sample	Increased emphasis on the volume of sample required within resources and from researcher at pre-testing meeting. Researchers to stress the importance of allowing disinfectant on the finger prick site to dry and drinking a sufficient amount of water prior to collection to minimise risk of sample haemolysis.	Missing lipid blood collection data was reduced (11% at T2, 23% at T3, 18% at T4).

7.4.4. The Impact of COVID-19 On Maternal Wellbeing

The COVID-19 pandemic also presented many difficulties for pregnant females, specifically, as they were identified as a *vulnerable group* to the virus (Di Mascio et al., 2020) and advised to take additional precautions to prevent infection. Prevalence of increased anxiety and depressive symptoms during pregnancy have been associated with COVID-19 related worries (Lebel et al., 2020). Moreover, pregnant females did not have the 'pregnancy experience' they envisioned, which may increase feelings of anxiety and depression. Interview data from *Chapter 6* provided significant insight into female's perceptions of COVID-19 and its impact on their pregnancy experience. Likewise, to Karavadra and colleagues (2020), several pregnant participants expressed concern about a hospital delivery due to fear of COVID-19 and uncertainty regarding restrictions, leaving several contemplating a home birth. The uncertainty regarding restrictions and frequent modification of rules for pregnant females may negatively impact female's emotional wellbeing (Giurgescu et al., 2006). Furthermore, research has suggested that females with prenatal depression are at a higher risk of poor diet quality compared with pregnant females without prenatal depression (Avalos et al., 2020). Therefore, increased prevalence of anxiety and depressive symptoms due to the COVID-19 pandemic in pregnant females may negatively impact nutrition, and consequently have an influence on glucose control measured in *Chapter 5*. Notably however, participants in *Chapter 6* recorded low levels of anxiety and depression. Thus, findings from interviews in *Chapter 6* and influences on glucose control in *Chapter 5* may be more pronounced in pregnant females with higher anxiety and depression scores.

7.5. Implications of Findings

The key implications of the work within this thesis are presented in Table 7.2.

Table 7.2. Implications of Findings.

Major Finding	Implication
Remote data collection is feasible	Remote data collection should be viewed as an important and feasible facilitator to target individuals who typically lack access to and knowledge about clinical trials. Continuation of remote data collection can enable involvement and, thus, representation of hard-to-reach populations like rural residents and those living a great distance from research facilities. Furthermore, remote data collection could be adopted within healthcare if proven valid, reliable, and economically viable within this setting. This practise could decrease health disparities and promote future health equity.
Importance of direct psychosocial support and clear, trustworthy information to increase antenatal exercise for pregnant females.	These findings can be used to inform future development of comprehensive and appropriate promotional strategies for antenatal exercise.
Semi-structured interviews revealed that pregnant females found it difficult to find time to exercise.	Findings from *Chapter 4,* for example positive participant perceptions of the exercise intervention including guidance, social support, and flexibility, provide rationale to investigate whether the same home-based intervention could be an effective strategy to increase PA in pregnant females.

Non-significant decrease in glucose variability at postpartum in comparison to during pregnancy.	These data imply that glucose control may be compromised during pregnancy, perhaps to support the needs of the growing foetus.
No relationship between PA and glucose control was observed across the perinatal period.	It is possible that this occurred due to low levels of PA recorded at all timepoints. These low levels of PA reported in females across the perinatal period may have been driven by COVID-19 restrictions.

PA; physical activity, COVID-19; corona-virus pandemic 2019.

7.6. Methodological Considerations and Limitations

There are several strengths in the methodology of this thesis. *Chapter 4* is the first exercise/PA intervention study to our knowledge to employ a wholly remote study design, and therefore the feasibility of this approach was assessed. Moreover, to the authors knowledge, *Chapter 5* is the first study to investigate glucose variability across the perinatal period and assess the relationship between PA and glucose control disaggregated by trimester and postpartum. Additionally, *Chapter 6* utilised a rich and in-depth approach, via thematic analysis of semi-structured interviews, to directly explore the perceptions of antenatal exercise in pregnant females and the impact of the COVID-19 pandemic on their pregnancy experience. Remote data collection allowed nationwide participation in all studies in this thesis, therefore allowing capture of a representation of the UK population and increased access and inclusivity in studies in those from a range of socioeconomic backgrounds. Furthermore, a thematic analysis approach as detailed by Braun and Clarke (2006) is a rigorous strategy that produced an insightful analysis of semi-structured interview data.

Despite these methodological strengths, several limitations are also apparent within this thesis. Firstly, remote data collection employed in C*hapters 4 and 5* prohibited the ability to ensure control of diet and exercise prior to testing measurements. Moreover, the interventions employed within *Chapter 4* required participants to have access to a smartphone and Wi-Fi/data plan, therefore may have excluded participation from exceptionally low socioeconomic groups. Additionally, although the researcher provided participants in *Chapters 4 and 5* with detailed verbal and written information regarding how to perform the testing measurements, it is unknown whether participants recorded and reported data correctly. *Chapters 4* and *5* also collected CGM over 7 consecutive days, despite guidelines recommending 14 days of wear to allow broad glucose assessment. Reducing wear-time from 14 to 7 days was decided to reduce participant burden whilst maintaining inclusion of weekdays and weekend days. In *Chapter 4*, CGM data obtained was not disaggregated for sex, despite NIH guidance (National Institutes of Health, 2015), due to the feasibility study design. Therefore, there was a lack of understanding of sex-specific physiological differences to the exercise intervention conducted. However, unsurprisingly, limited changes were observed in both sexes in response to a 12-week exercise intervention due to the healthy, albeit sedentary, participant group.

No follow-up data were collected following the 12-week exercise interventions in *Chapter 4*. Therefore, it is unknown whether the exercise intervention strategies employed are effective in eliciting a behaviour change or if feedback and monitors were exclusively responsible for short-term changes in habitual activity behaviours. This, consequently, restricts understanding of the long-term effects of the prescribed exercise. Based on the preliminary effectiveness findings from this Chapter, RCTs employing the same intervention design should be conducted with a follow-up assessment at 3 months and 1-year post-intervention to investigate medium-term and long-term behaviour change, respectively. Due to remote data collection strategies employed throughout this thesis, semi-structured interviews in *Chapter 6* were conducted via phone or video call. This meant that external influences (i.e. children, partner) could not be controlled. Therefore, external influences may have affected participant's interview answers and restricted deeper conversations regarding peer support.

Furthermore, findings in *Chapter 5* may be in part attributed to relaxation of government restrictions that aimed to reduce the transmission of COVID-19. Similarly, changes in PA observed in *Chapter 4* may also be attributed to changes in government restrictions. Therefore, we cannot make causal inference from these data. Semi-structured interviews were conducted between November 2020 and May 2021, encompassing a period whereby restrictions were frequently changing. These restrictions included two separate national lockdowns as well as local lockdowns (Institute for Government, 2021). Perceived barriers to antenatal exercise and perceptions of the pregnancy experience may therefore be specific to a particular time certain restrictions were in place. Subsequently, caution should be applied when relating these findings to all pregnant females.

7.7. Recommendations for Future Directions

Based on the evidence presented in this thesis, there are several key areas in which future studies can build upon to enhance understanding further.

1. Further examination of the validity and reproducibility of remote data collection is required. Laboratory data should be collected in a short time frame to home-based collected data for comparison. This work is currently underway in our laboratory.

2. Further examination of the validity of CRF estimation using mHealth technologies for use within remote clinical research would provide greater insight to the effectiveness of home-based exercise interventions and their efficacy to decrease all-cause mortality.

3. Based on findings in *Chapter 4,* a definitive RCT should explore the effectiveness of a home-based exercise intervention using mHealth technology and exercise counselling to improve PA and health outcomes, assessed using remote data collection techniques, in sedentary individuals.

4. Further to *Chapter 5,* large-scale longitudinal studies, incorporating monitoring of sleep, diet, and 24-hour PA during pregnancy with GDM and postpartum following GDM, should be conducted to confirm whether a relationship between PA and glucose control exists across the perinatal period in this population.

5. Building on point 4*,* a study including a supervised exercise intervention during pregnancy with GDM, which aims to achieve 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity PA per week, should determine the influence of exercise intensity on the relationship between PA and glucose control.

6. Based on findings detailed within *Chapter 6,* efforts to enhance pregnant female's awareness and understanding of the UK antenatal PA guidelines should be considered a priority, central to this is HCP and midwifery education on antenatal PA and exercise. Future research should aim to design and systematically evaluate the implementation and impact of such promotional strategies that take into consideration pregnant female's perceived barriers and facilitators to exercise.

CHAPTER 8: REFERENCES

ABEL, K. M., HOPE, H., SWIFT, E., PARISI, R., ASHCROFT, D. M., KOSIDOU, K., OSAM, C. S., DALMAN, C. & PIERCE, M. 2019. Prevalence of maternal mental illness among children and adolescents in the UK between 2005 and 2017: a national retrospective cohort analysis. *The Lancet Public Health,* 4**,** e291-e300.

ACTIVE PREGNANCY FOUNDATION 2020. Preliminary Findings from the 'Pregnancy and Physical Activity during the COVID-19 Pandemic' Survey. Unpublished: Active Pregnancy Foundation: Kingston upon Thames, UK.

AFOLABI, B., ABUDU, O. & OYEYINKA, O. 2003. Fasting plasma glucose levels in normal pregnant Nigerians. *Journal of obstetrics and Gynaecology,* 23**,** 640-642.

AHMED, H. M., BLAHA, M. J., NASIR, K., RIVERA, J. J. & BLUMENTHAL, R. S. 2012. Effects of physical activity on cardiovascular disease. *The American journal of cardiology,* 109**,** 288-295.

AKIKI, S., AVISON, W. R., SPEECHLEY, K. N. & CAMPBELL, M. K. 2016. Determinants of maternal antenatal state-anxiety in mid-pregnancy: Role of maternal feelings about the pregnancy. *Journal of affective disorders,* 196**,** 260-267.

ALTMAN, M. R., GAVIN, A. R., EAGEN-TORKKO, M. K., KANTROWITZ-GORDON, I., KHOSA, R. M. & MOHAMMED, S. A. 2021. Where the system failed: the COVID-19 pandemic's impact on pregnancy and birth care. *Global Qualitative Nursing Research,* 8**,** 23333936211006397.

AMERICAN DIABETES ASSOCIATION 2015. 12. Management of diabetes in pregnancy. *Diabetes care,* 38**,** S77-S79.

AUNE, D., SEN, A., HENRIKSEN, T., SAUGSTAD, O. D. & TONSTAD, S. 2016. Physical activity and the risk of gestational diabetes mellitus: a systematic review and dose–response meta-analysis of epidemiological studies. *European journal of epidemiology,* 31**,** 967-997.

AVALOS, L. A., CAAN, B., NANCE, N., ZHU, Y., LI, D.-K., QUESENBERRY, C., HYDE, R. J. & HEDDERSON, M. M. 2020. Prenatal depression and diet quality during pregnancy. *Journal of the Academy of Nutrition and Dietetics,* 120**,** 972-984.

BACHMANN, C., OESCH, P. & BACHMANN, S. 2018. Recommendations for improving adherence to home-based exercise: a systematic review. *Physikalische Medizin, Rehabilitationsmedizin, Kurortmedizin,* 28**,** 20-31.

BACIGALUPO, R., CUDD, P., LITTLEWOOD, C., BISSELL, P., HAWLEY, M. & BUCKLEY WOODS, H. 2013. Interventions employing mobile technology for overweight and obesity: an early systematic review of randomized controlled trials. *Obesity reviews,* 14**,** 279-291.

BATTELINO, T., DANNE, T., BERGENSTAL, R. M., AMIEL, S. A., BECK, R., BIESTER, T., BOSI, E., BUCKINGHAM, B. A., CEFALU, W. T. & CLOSE, K. L. 2019. Clinical targets for continuous glucose monitoring data interpretation: recommendations from the international consensus on time in range. *Diabetes care,* 42**,** 1593-1603.

BAUER, C., GRAF, C., PLATSCHEK, A. M., STRÜDER, H. K. & FERRARI, N. 2018. Reasons, motivational factors, and perceived personal barriers to engagement in physical activity during pregnancy vary within the BMI classes: The Prenatal Prevention Project Germany. *Journal of Physical Activity and Health,* 15**,** 204-211.

BEDDOE, A. E., YANG, C.-P. P., KENNEDY, H. P., WEISS, S. J. & LEE, K. A. 2009. The effects of mindfulness-based yoga during pregnancy on maternal psychological and physical distress. *Journal of Obstetric, Gynecologic & Neonatal Nursing,* 38**,** 310-319.

BEHRAVESH, M., FERNANDEZ-TAJES, J., ESTAMPADOR, A. C., VARGA, T. V., GUNNARSSON, Ó. S., STREVENS, H., TIMPKA, S. & FRANKS, P. W. 2021. A prospective study of the relationships between movement and glycemic control during day and night in pregnancy. *Scientific reports,* 11**,** 1-10.

BILLINGHAM, S. A., WHITEHEAD, A. L. & JULIOUS, S. A. 2013. An audit of sample sizes for pilot and feasibility trials being undertaken in the United Kingdom registered in the United Kingdom Clinical Research Network database. *BMC medical research methodology,* 13**,** 1-6.

BIVIÁ-ROIG, G., LA ROSA, V. L., GÓMEZ-TÉBAR, M., SERRANO-RAYA, L., AMER-CUENCA, J. J., CARUSO, S., COMMODARI, E., BARRASA-SHAW, A. & LISÓN, J. F. 2020. Analysis of the impact of the confinement resulting from COVID-19 on the lifestyle and psychological wellbeing of Spanish pregnant women: an Internet-based cross-sectional survey. *International Journal of Environmental Research and Public Health,* 17**,** 5933.

BO, S., ROSATO, R., CICCONE, G., CANIL, S., GAMBINO, R., POALA, C. B., LEONE, F., VALLA, A., GRASSI, G. & GHIGO, E. 2014. Simple lifestyle recommendations and the outcomes of gestational diabetes. A 2× 2 factorial randomized trial. *Diabetes, obesity and metabolism,* 16**,** 1032-1035.

BORODULIN, K., EVENSON, K. R. & HERRING, A. H. 2009. Physical activity patterns during pregnancy through postpartum. *BMC women's health,* 9**,** 1-7.

BORODULIN, K., EVENSON, K. R., WEN, F., HERRING, A. H. & BENSON, A. 2008. Physical activity patterns during pregnancy. *Medicine and science in sports and exercise,* 40**,** 1901.

BOZIONELOS, G. & BENNETT, P. 1999. The theory of planned behaviour as predictor of exercise: The moderating influence of beliefs and personality variables. *Journal of health psychology,* 4**,** 517-529.

BRADLEY, N. L., DIPASQUALE, A. M., DILLABOUGH, K. & SCHNEIDER, P. S. 2020. Health care practitioners' responsibility to address intimate partner violence related to the COVID-19 pandemic. *Cmaj,* 192**,** E609-E610.

BRAUN, V. & CLARKE, V. 2006. Using thematic analysis in psychology. *Qualitative research in psychology,* 3**,** 77-101.

BRICKWOOD, K.-J., WATSON, G., O'BRIEN, J. & WILLIAMS, A. D. 2019. Consumer-based wearable activity trackers increase physical activity participation: systematic review and meta-analysis. *JMIR mHealth and uHealth,* 7**,** e11819.

BRISLANE, Á., LARKIN, F., JONES, H. & DAVENPORT, M. H. 2021. Access to and Quality of Healthcare for Pregnant and Postpartum Women During the COVID-19 Pandemic. *Frontiers in Global Women's Health,* 2**,** 3.

BROWN, M. J., SINCLAIR, M., LIDDLE, S. D., HILL, A. J., STOCKDALE, D. J. & MADDEN, E. 2013. Motivating pregnant women to eat healthily and engage in physical activity for weight management: an exploration of routine midwife instruction. *Evidence Based Midwifery,* 11**,** 120-127.

BUCHANAN, T. A., XIANG, A. H. & PAGE, K. A. 2012. Gestational diabetes mellitus: risks and management during and after pregnancy. *Nature Reviews Endocrinology,* 8**,** 639.

BUTLER, C. L., WILLIAMS, M. A., SORENSEN, T. K., FREDERICK, I. O. & LEISENRING, W. M. 2004. Relation between maternal recreational physical activity and plasma lipids in early pregnancy. *American journal of epidemiology,* 160**,** 350-359.

BUTTE, N. F. 2000. Carbohydrate and lipid metabolism in pregnancy: normal compared with gestational diabetes mellitus. *The American journal of clinical nutrition,* 71**,** 1256S-1261S.

BYBERG, S., HANSEN, A. L., CHRISTENSEN, D. L., VISTISEN, D., AADAHL, M., LINNEBERG, A. & WITTE, D. R. 2012. Sleep duration and sleep quality are associated differently with alterations of glucose homeostasis. *Diabetic Medicine,* 29**,** e354-e360.

CAMPBELL, M. K. & MOTTOLA, M. F. 2001. Recreational exercise and occupational activity during pregnancy and birth weight: a case-control study. *American Journal of Obstetrics and Gynecology,* 184**,** 403-408.

CARRIER, B., CREER, A., WILLIAMS, L. R., HOLMES, T. M., JOLLEY, B. D., DAHL, S., WEBER, E. & STANDIFIRD, T. 2020. Validation of garmin fenix 3 HR fitness tracker biomechanics and metabolics (VO2max). *Journal for the Measurement of Physical Behaviour,* 3**,** 331-337.

CARTER, L. G., LEWIS, K. N., WILKERSON, D. C., TOBIA, C. M., NGO TENLEP, S. Y., SHRIDAS, P., GARCIA-CAZARIN, M. L., WOLFF, G., ANDRADE, F. H. & CHARNIGO, R. J. 2012. Perinatal exercise improves glucose homeostasis in adult offspring. *American Journal of Physiology-Endocrinology and Metabolism,* 303**,** E1061-E1068.

CATALANO, P. M., HUSTON, L., AMINI, S. B. & KALHAN, S. C. 1999. Longitudinal changes in glucose metabolism during pregnancy in obese women with normal glucose tolerance and gestational diabetes mellitus. *American journal of obstetrics and gynecology,* 180**,** 903-916.

CHAN, C. B., RYAN, D. A. & TUDOR-LOCKE, C. 2004. Health benefits of a pedometer-based physical activity intervention in sedentary workers. *Preventive medicine,* 39**,** 1215-1222.

CHAN, K. L. & CHEN, M. 2019. Effects of social media and mobile health apps on pregnancy care: meta-analysis. *JMIR mHealth and uHealth,* 7**,** e11836.

CHASAN-TABER, L., SCHMIDT, M. D., PEKOW, P., STERNFELD, B., MANSON, J. & MARKENSON, G. 2007. Correlates of physical activity in pregnancy among Latina women. *Maternal and child health journal,* 11**,** 353-363.

CHEN, N., ZHOU, M., DONG, X., QU, J., GONG, F., HAN, Y., QIU, Y., WANG, J., LIU, Y. & WEI, Y. 2020. Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *The lancet,* 395**,** 507-513.

CHIEF MEDICAL OFFICERS 2019. UK Chief Medical Officers' Physical Activity Guidelines.

CHMIELEWSKA, B., BARRATT, I., TOWNSEND, R., KALAFAT, E., VAN DER MEULEN, J., GUROL-URGANCI, I., O'BRIEN, P., MORRIS, E., DRAYCOTT, T. & THANGARATINAM, S. 2021. Effects of the COVID-19 pandemic on maternal and perinatal outcomes: a systematic review and meta-analysis. *The Lancet Global Health*.

CIOFFI, J., SCHMIED, V., DAHLEN, H., MILLS, A., THORNTON, C., DUFF, M., CUMMINGS, J. & KOLT, G. S. 2010. Physical activity in pregnancy: women's perceptions, practices, and influencing factors. *Journal of midwifery & women's health,* 55**,** 455-461.

CLAPP III, J. F. 2008. Long-term outcome after exercising throughout pregnancy: fitness and cardiovascular risk. *American journal of obstetrics and gynecology,* 199**,** 489. e1-489. e6.

CLARKE, P., ROUSHAM, E., GROSS, H., HALLIGAN, A. & BOSIO, P. 2005. Activity patterns and time allocation during pregnancy: a longitudinal study of British women. *Annals of Human Biology,* 32**,** 247-258.

CLARKE, P. E. & GROSS, H. 2004. Women's behaviour, beliefs and information sources about physical exercise in pregnancy. *Midwifery,* 20**,** 133-141.

COHEN, J. 1988. *Statistical Power Analysis for the Behavioral Sciences (2nd ed.).* , Hillside NJ: Lawrence Erlbaum Associates.

COHEN, S. 2004. Social relationships and health. *American psychologist,* 59**,** 676.

COLL, C., DOMINGUES, M., SANTOS, I., MATIJASEVICH, A., HORTA, B. L. & HALLAL, P. C. 2016. Changes in leisure-time physical activity from the prepregnancy to the postpartum period: 2004 Pelotas (Brazil) Birth Cohort Study. *Journal of physical activity and health,* 13**,** 361-365.

COLLEY, R. C., GARRIGUET, D., JANSSEN, I., CRAIG, C. L., CLARKE, J. & TREMBLAY, M. S. 2011. Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. *Health reports,* 22**,** 7.

COMMITTEE ON OBSTETRIC PRACTICE 2002. ACOG committee opinion. Exercise during pregnancy and the postpartum period. Number 267, January 2002. American College of Obstetricians and Gynecologists. *International journal of gynaecology and obstetrics: the official organ of the International Federation of Gynaecology and Obstetrics,* 77**,** 79-81.

COSTA-FONT, J., HERNÁNDEZ-QUEVEDO, C. & MCGUIRE, A. 2011. Persistence despite action? Measuring the patterns of health inequality in England (1997–2007). *Health Policy,* 103**,** 149-159.

CRAIG, C. L., MARSHALL, A. L., SJÖSTRÖM, M., BAUMAN, A. E., BOOTH, M. L., AINSWORTH, B. E., PRATT, M., EKELUND, U., YNGVE, A. & SALLIS, J. F. 2003. International physical activity questionnaire: 12-country reliability and validity. *Medicine & science in sports & exercise,* 35**,** 1381-1395.

CRAMP, A. G. & BRAY, S. R. 2009. A prospective examination of exercise and barrier self-efficacy to engage in leisure-time physical activity during pregnancy. *Annals of Behavioral Medicine,* 37**,** 325-334.

DA COSTA, D. & IRELAND, K. 2013. Perceived benefits and barriers to leisure-time physical activity during pregnancy in previously inactive and active women. *Women & health,* 53**,** 185-202.

DANNE, T., NIMRI, R., BATTELINO, T., BERGENSTAL, R. M., CLOSE, K. L., DEVRIES, J. H., GARG, S., HEINEMANN, L., HIRSCH, I. & AMIEL, S. A. 2017. International consensus on use of continuous glucose monitoring. *Diabetes care,* 40**,** 1631-1640.

DAVENPORT, M. H., MCCURDY, A. P., MOTTOLA, M. F., SKOW, R. J., MEAH, V. L., POITRAS, V. J., GARCIA, A. J., GRAY, C. E., BARROWMAN, N. & RISKE, L. 2018a. Impact of prenatal exercise on both prenatal and postnatal anxiety and depressive symptoms: a systematic review and meta-analysis. *British journal of sports medicine,* 52**,** 1376-1385.

DAVENPORT, M. H., MEYER, S., MEAH, V. L., STRYNADKA, M. C. & KHURANA, R. 2020. Moms are not OK: COVID-19 and maternal mental health. *Frontiers in global women's health,* 1**,** 1.

DAVENPORT, M. H., MOTTOLA, M. F., MCMANUS, R. & GRATTON, R. 2008. A walking intervention improves capillary glucose control in women with gestational diabetes mellitus: a pilot study. *Applied physiology, nutrition, and metabolism,* 33**,** 511-517.

DAVENPORT, M. H., RUCHAT, S.-M., POITRAS, V. J., GARCIA, A. J., GRAY, C. E., BARROWMAN, N., SKOW, R. J., MEAH, V. L., RISKE, L. & SOBIERAJSKI, F. 2018b. Prenatal exercise for the prevention of gestational diabetes mellitus and hypertensive disorders of pregnancy: a systematic review and meta-analysis. *Br J Sports Med,* 52**,** 1367-1375.

DAVENPORT, M. H., SKOW, R. J. & STEINBACK, C. D. 2016. Maternal Responses to Aerobic Exercise in Pregnancy. *Clin Obstet Gynecol,* 59**,** 541-51.

DAVENPORT, M. H., SOBIERAJSKI, F., MOTTOLA, M. F., SKOW, R. J., MEAH, V. L., POITRAS, V. J., GRAY, C. E., GARCIA, A. J., BARROWMAN, N. & RISKE, L. 2018c. Glucose responses to acute and chronic exercise during pregnancy: a systematic review and meta-analysis. *British journal of sports medicine,* 52**,** 1357-1366.

DAVIES, G. A., WOLFE, L. A., MOTTOLA, M. F. & MACKINNON, C. 2003. Joint SOGC/CSEP clinical practice guideline: exercise in pregnancy and the postpartum period. *Canadian Journal of Applied Physiology,* 28**,** 329-341.

DE VIVO, M. & MILLS, H. 2019. "They turn to you first for everything": insights into midwives' perspectives of providing physical activity advice and guidance to pregnant women. *BMC pregnancy and childbirth,* 19**,** 1-12.

DELL'UTRI, C., MANZONI, E., CIPRIANI, S., SPIZZICO, C., DELL'ACQUA, A., BARBARA, G., PARAZZINI, F. & KUSTERMANN, A. 2020. Effects of SARS Cov-2 epidemic on the obstetrical and gynecological emergency service accesses. What happened and what shall we expect now? *European Journal of Obstetrics & Gynecology and Reproductive Biology,* 254**,** 64-68.

DEMISSIE, Z., SIEGA-RIZ, A. M., EVENSON, K. R., HERRING, A. H., DOLE, N. & GAYNES, B. N. 2011. Physical activity and depressive symptoms among pregnant women: the PIN3 study. *Archives of women's mental health,* 14**,** 145-157.

DEVLIN, J. T., HIRSHMAN, M., HORTON, E. D. & HORTON, E. S. 1987. Enhanced peripheral and splanchnic insulin sensitivity in NIDDM men after single bout of exercise. *Diabetes,* 36**,** 434-439.

DI MASCIO, D., KHALIL, A., SACCONE, G., RIZZO, G., BUCA, D., LIBERATI, M., VECCHIET, J., NAPPI, L., SCAMBIA, G. & BERGHELLA, V. 2020. Outcome of coronavirus spectrum infections (SARS, MERS, COVID-19) during pregnancy: a systematic review and meta-analysis. *American journal of obstetrics & gynecology MFM,* 2**,** 100107.

DING, D., DEL POZO CRUZ, B., GREEN, M. A. & BAUMAN, A. E. 2020. Is the COVID-19 lockdown nudging people to be more active: a big data analysis. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

DING, D., LAWSON, K. D., KOLBE-ALEXANDER, T. L., FINKELSTEIN, E. A., KATZMARZYK, P. T., VAN MECHELEN, W., PRATT, M. & COMMITTEE, L. P. A. S. E. 2016. The economic burden of physical inactivity: a global analysis of major non-communicable diseases. *The Lancet,* 388**,** 1311-1324.

DOHERTY, A., JACKSON, D., HAMMERLA, N., PLÖTZ, T., OLIVIER, P., GRANAT, M. H., WHITE, T., VAN HEES, V. T., TRENELL, M. I. & OWEN, C. G. 2017. Large scale population assessment of physical activity using wrist worn accelerometers: the UK biobank study. *PloS one,* 12**,** e0169649.

DORAN, F. & O'BRIEN, A. P. 2007. A brief report of attitudes towards physical activity during pregnancy. *Health Promotion Journal of Australia,* 18**,** 155-158.

DOWNS, D. S. & HAUSENBLAS, H. A. 2004. Women's exercise beliefs and behaviors during their pregnancy and postpartum. *Journal of midwifery & women's health,* 49**,** 138-144.

DRENOWATZ, C., PRASAD, V. K., HAND, G. A., SHOOK, R. P. & BLAIR, S. N. 2016. Effects of moderate and vigorous physical activity on fitness and body composition. *Journal of Behavioral Medicine,* 39**,** 624-632.

DUNCOMBE, D., WERTHEIM, E. H., SKOUTERIS, H., PAXTON, S. J. & KELLY, L. 2009. Factors related to exercise over the course of pregnancy including women's beliefs about the safety of exercise during pregnancy. *Midwifery,* 25**,** 430-438.

EADES, C. E., CAMERON, D. M. & EVANS, J. M. 2017. Prevalence of gestational diabetes mellitus in Europe: A meta-analysis. *Diabetes research and clinical practice,* 129**,** 173-181.

EAMES, M., BEN-SHLOMO, Y. & MARMOT, M. G. 1993. Social deprivation and premature mortality: regional comparison across England. *British Medical Journal,* 307**,** 1097-1102.

EAPEN, Z. J. & PETERSON, E. D. 2015. Can mobile health applications facilitate meaningful behavior change?: time for answers. *Jama,* 314**,** 1236-1237.

EKELUND, U., BESSON, H., LUAN, J. A., MAY, A. M., SHARP, S. J., BRAGE, S., TRAVIER, N., AGUDO, A., SLIMANI, N. & RINALDI, S. 2011. Physical activity and gain in abdominal adiposity and body weight: prospective cohort study in 288,498 men and women. *The American journal of clinical nutrition,* 93**,** 826-835.

EL-RAFIE, M. M., KHAFAGY, G. M. & GAMAL, M. G. 2016. Effect of aerobic exercise during pregnancy on antenatal depression. *International journal of women's health,* 8**,** 53.

ENGLERT, K., RUEDY, K., COFFEY, J., CASWELL, K., STEFFEN, A., LEVANDOSKI, L. & GROUP, D. R. I. C. S. 2014. Skin and adhesive issues with continuous glucose monitors: a sticky situation. *Journal of diabetes science and technology,* 8**,** 745-751.

EVANS, J., HERON, J., FRANCOMB, H., OKE, S. & GOLDING, J. 2001. Cohort study of depressed mood during pregnancy and after childbirth. *Bmj,* 323**,** 257-260.

EVENSON, K. R., MOOS, M.-K., CARRIER, K. & SIEGA-RIZ, A. M. 2009. Perceived barriers to physical activity among pregnant women. *Maternal and child health journal,* 13**,** 364.

FADNES, L. T., TAUBE, A. & TYLLESKÄR, T. 2009. How to identify information bias due to self-reporting in epidemiological research. *The Internet Journal of Epidemiology,* 7**,** 28-38.

FARRELL, T., REAGU, S., MOHAN, S., ELMIDANY, R., QADDOURA, F., AHMED, E. E., CORBETT, G., LINDOW, S., ABUYAQOUB, S. M. & ALABDULLA, M. A. 2020. The impact of the COVID-19 pandemic on the perinatal mental health of women. *Journal of Perinatal Medicine,* 48**,** 971-976.

FIELD, T., DIEGO, M., DELGADO, J. & MEDINA, L. 2013a. Tai chi/yoga reduces prenatal depression, anxiety and sleep disturbances. *Complementary therapies in clinical practice,* 19**,** 6-10.

FIELD, T., DIEGO, M., DELGADO, J. & MEDINA, L. 2013b. Yoga and social support reduce prenatal depression, anxiety and cortisol. *Journal of bodywork and movement therapies,* 17**,** 397-403.

FIELD, T., DIEGO, M., HERNANDEZ-REIF, M., MEDINA, L., DELGADO, J. & HERNANDEZ, A. 2012. Yoga and massage therapy reduce prenatal depression and prematurity. *Journal of bodywork and movement therapies,* 16**,** 204-209.

FINKELSTEIN, E. A., HAALAND, B. A., BILGER, M., SAHASRANAMAN, A., SLOAN, R. A., NANG, E. E. K. & EVENSON, K. R. 2016. Effectiveness of activity trackers with and without incentives to increase physical activity (TRIPPA): a randomised controlled trial. *The lancet Diabetes & endocrinology,* 4**,** 983-995.

FLANNERY, C., MCHUGH, S., ANABA, A. E., CLIFFORD, E., O'RIORDAN, M., KENNY, L. C., MCAULIFFE, F. M., KEARNEY, P. M. & BYRNE, M. 2018. Enablers and barriers to physical activity in overweight and obese pregnant women: an analysis informed by the theoretical domains framework and COM-B model. *BMC pregnancy and childbirth,* 18**,** 1-13.

FORD, E. S., COWIE, C. C., LI, C., HANDELSMAN, Y. & BLOOMGARDEN, Z. T. 2011. Iron-deficiency anemia, non-iron-deficiency anemia and HbA1c among adults in the US*. *Journal of Diabetes,* 3**,** 67-73.

FRANSSON, E., ÖRTENSTRAND, A. & HJELMSTEDT, A. 2011. Antenatal depressive symptoms and preterm birth: a prospective study of a Swedish national sample. *Birth,* 38**,** 10-16.
FREEBERG, K. A., BAUGHMAN, B. R., VICKEY, T., SULLIVAN, J. A. & SAWYER, B. J. 2019. Assessing the ability of the Fitbit Charge 2 to accurately predict VO2max. *Mhealth,* 5.
FRIEDMAN, L. E., GELAYE, B., SANCHEZ, S. E. & WILLIAMS, M. A. 2020. Association of social support and antepartum depression among pregnant women. *Journal of affective disorders,* 264**,** 201-205.
GALTIER, F. 2010. Definition, epidemiology, risk factors. *Diabetes & metabolism,* 36**,** 628-651.
GARRISON, A. 2015. Screening, diagnosis, and management of gestational diabetes mellitus. *American family physician,* 91**,** 460-467.
GAVIN, N. I., GAYNES, B. N., LOHR, K. N., MELTZER-BRODY, S., GARTLEHNER, G. & SWINSON, T. 2005. Perinatal depression: a systematic review of prevalence and incidence. *Obstetrics & Gynecology,* 106**,** 1071-1083.
GEWIN, V. 2020. The career cost of COVID-19 to female researchers, and how science should respond. Nature Publishing Group.
GIURGESCU, C., PENCKOFER, S., MAURER, M. C. & BRYANT, F. B. 2006. Impact of uncertainty, social support, and prenatal coping on the psychological well-being of high-risk pregnant women. *Nursing research,* 55**,** 356-365.
GJESTLAND, K., BØ, K., OWE, K. M. & EBERHARD-GRAN, M. 2013. Do pregnant women follow exercise guidelines? Prevalence data among 3482 women, and prediction of low-back pain, pelvic girdle pain and depression. *British journal of sports medicine,* 47**,** 515-520.
GONG, X., HAO, J., TAO, F., ZHANG, J., WANG, H. & XU, R. 2013. Pregnancy loss and anxiety and depression during subsequent pregnancies: data from the C-ABC study. *European Journal of Obstetrics & Gynecology and Reproductive Biology,* 166**,** 30-36.
GONZÁLEZ-RODRÍGUEZ, M., PAZOS-COUSELO, M., GARCÍA-LÓPEZ, J. M., RODRÍGUEZ-SEGADE, S., RODRÍGUEZ-GARCÍA, J., TÚÑEZ-BASTIDA, C. & GUDE, F. 2019. Postprandial glycemic response in a non-diabetic adult population: the effect of nutrients is different between men and women. *Nutrition & metabolism,* 16**,** 1-9.
GOYAL, M., SINGH, P., SINGH, K., SHEKHAR, S., AGRAWAL, N. & MISRA, S. 2021. The effect of the COVID-19 pandemic on maternal health due to delay in seeking health care: experience from a tertiary center. *International Journal of Gynecology & Obstetrics,* 152**,** 231-235.
GRADMARK, A., POMEROY, J., RENSTRÖM, F., STEIGINGA, S., PERSSON, M., WRIGHT, A., BLUCK, L., DOMELLÖF, M., KAHN, S. E. & MOGREN, I. 2011. Physical activity, sedentary behaviors, and estimated insulin sensitivity and secretion in pregnant and non-pregnant women. *BMC pregnancy and childbirth,* 11**,** 1-8.
GRATTAN, D. R. & LADYMAN, S. R. 2020. Chapter 2 - Neurophysiological and cognitive changes in pregnancy. *In:* STEEGERS, E. A. P., CIPOLLA, M. J. & MILLER, E. C. (eds.) *Handbook of Clinical Neurology.* Elsevier.
GRIGORIADIS, S., GRAVES, L., PEER, M., MAMISASHVILI, L., TOMLINSON, G., VIGOD, S. N., DENNIS, C.-L., STEINER, M., BROWN, C. & CHEUNG, A. 2018. Maternal anxiety during pregnancy and the association with adverse perinatal outcomes: systematic review and meta-analysis. *The Journal of clinical psychiatry,* 79**,** 813.
GROTE, N. K., BRIDGE, J. A., GAVIN, A. R., MELVILLE, J. L., IYENGAR, S. & KATON, W. J. 2010. A meta-analysis of depression during pregnancy and the risk of preterm

birth, low birth weight, and intrauterine growth restriction. *Archives of general psychiatry,* 67**,** 1012-1024.
GU, X.-X., CHEN, K., YU, H., LIANG, G.-Y., CHEN, H. & SHEN, Y. 2020. How to prevent in-hospital COVID-19 infection and reassure women about the safety of pregnancy: experience from an obstetric center in China. *Journal of International Medical Research,* 48**,** 0300060520939337.
GUNDERSON, E. P., CRITES, Y., CHIANG, V., WALTON, D., AZEVEDO, R. A., FOX, G., ELMASIAN, C., YOUNG, S., SALVADOR, N. & LUM, M. 2012. Influence of breastfeeding during the postpartum oral glucose tolerance test on plasma glucose and insulin. *Obstetrics and gynecology,* 120**,** 136.
HAAKSTAD, L. A., VOLDNER, N., HENRIKSEN, T. & BØ, K. 2009. Why do pregnant women stop exercising in the third trimester? *Acta obstetricia et gynecologica Scandinavica,* 88**,** 1267-1275.
HAGSTRÖMER, M., OJA, P. & SJÖSTRÖM, M. 2007. Physical activity and inactivity in an adult population assessed by accelerometry. *Medicine and science in sports and exercise,* 39**,** 1502-1508.
HAHN, V., HALLE, M., SCHMIDT-TRUCKSASS, A., RATHMANN, W., MEISINGER, C. & MIELCK, A. 2009. Physical activity and the metabolic syndrome in elderly German men and women: results from the population-based KORA survey. *Diabetes Care,* 32**,** 511-513.
HAMER, M., STAMATAKIS, E. & STEPTOE, A. 2009. Dose-response relationship between physical activity and mental health: the Scottish Health Survey. *British journal of sports medicine,* 43**,** 1111-1114.
HAMMER, R. L., PERKINS, J. & PARR, R. 2000. Exercise during the childbearing year. *The Journal of perinatal education,* 9**,** 1-13.
HANGHØJ, S. 2013. When it hurts I think: Now the baby dies. Risk perceptions of physical activity during pregnancy. *Women and Birth,* 26**,** 190-194.
HANSEN, B. H., KOLLE, E., DYRSTAD, S. M., HOLME, I. & ANDERSSEN, S. A. 2012. Accelerometer-determined physical activity in adults and older people. *Medicine and science in sports and exercise,* 44**,** 266-272.
HARMON, K. A., GERARD, L., JENSEN, D. R., KEALEY, E. H., HERNANDEZ, T. L., REECE, M. S., BARBOUR, L. A. & BESSESEN, D. H. 2011. Continuous glucose profiles in obese and normal-weight pregnant women on a controlled diet: metabolic determinants of fetal growth. *Diabetes care,* 34**,** 2198-2204.
HARRIS, J. E., BAER, L. A. & STANFORD, K. I. 2018. Maternal exercise improves the metabolic health of adult offspring. *Trends in Endocrinology & Metabolism,* 29**,** 164-177.
HAWKINS, J., EDWARDS, M., CHARLES, J., JAGO, R., KELSON, M., MORGAN, K., MURPHY, S., OLIVER, E., SIMPSON, S. & EDWARDS, R. T. 2017. Protocol for a feasibility randomised controlled trial of the use of Physical ACtivity monitors in an Exercise Referral Setting: the PACERS study. *Pilot and Feasibility Studies,* 3**,** 1-12.
HAYASHI, A., MATSUZAKI, M., KUSAKA, M., SHIRAISHI, M. & HARUNA, M. 2016. Daily walking decreases casual glucose level among pregnant women in the second trimester. *Drug discoveries & therapeutics,* 10**,** 218-222.
HAYASHI, A., OGUCHI, H., KOZAWA, Y., BAN, Y., SHINODA, J. & SUGANUMA, N. 2018. Daily walking is effective for the management of pregnant women with gestational diabetes mellitus. *Journal of Obstetrics and Gynaecology Research,* 44**,** 1731-1738.
HEGAARD, H. K., KJAERGAARD, H., DAMM, P. P., PETERSSON, K. & DYKES, A.-K. 2010. Experiences of physical activity during pregnancy in Danish nulliparous women

with a physically active life before pregnancy. A qualitative study. *BMC Pregnancy and Childbirth,* 10**,** 33.
HEGDE, S. M. & SOLOMON, S. D. 2015. Influence of physical activity on hypertension and cardiac structure and function. *Current hypertension reports,* 17**,** 1-8.
HENDERSON, J. & REDSHAW, M. 2013. Anxiety in the perinatal period: antenatal and postnatal influences and women's experience of care. *Journal of Reproductive and Infant Psychology,* 31**,** 465-478.
HERON, J., O'CONNOR, T. G., EVANS, J., GOLDING, J., GLOVER, V. & TEAM, A. S. 2004. The course of anxiety and depression through pregnancy and the postpartum in a community sample. *Journal of affective disorders,* 80**,** 65-73.
HESKETH, K., JONES, H., KINNAFICK, F., SHEPHERD, S. O., WAGENMAKERS, A. J., STRAUSS, J. A. & COCKS, M. 2021. Home-Based HIIT and Traditional MICT Prescriptions Improve Cardiorespiratory Fitness to a Similar Extent Within an Exercise Referral Scheme for At-Risk Individuals. *Frontiers in physiology***,** 2015.
HESKETH, K. R. & EVENSON, K. R. 2016. Prevalence of US pregnant women meeting 2015 ACOG physical activity guidelines. *American journal of preventive medicine,* 51**,** e87-e89.
HESKETH, K. R., EVENSON, K. R., STROO, M., CLANCY, S. M., ØSTBYE, T. & BENJAMIN-NEELON, S. E. 2018. Physical activity and sedentary behavior during pregnancy and postpartum, measured using hip and wrist-worn accelerometers. *Preventive Medicine Reports,* 10**,** 337-345.
HILDEBRAND, M., HANSEN, B. H., VAN HEES, V. T. & EKELUND, U. 2017. Evaluation of raw acceleration sedentary thresholds in children and adults. *Scandinavian journal of medicine & science in sports,* 27**,** 1814-1823.
HILDEBRAND, M., VT, V. H., HANSEN, B. H. & EKELUND, U. 2014. Age group comparability of raw accelerometer output from wrist-and hip-worn monitors. *Medicine and science in sports and exercise,* 46**,** 1816-1824.
HINTON, P. S. & OLSON, C. M. 2001. Predictors of pregnancy-associated change in physical activity in a rural white population. *Maternal and child health journal,* 5**,** 7-14.
HODKINSON, A., KONTOPANTELIS, E., ADENIJI, C., VAN MARWIJK, H., MCMILLIAN, B., BOWER, P. & PANAGIOTI, M. 2021. Interventions using wearable physical activity trackers among adults with cardiometabolic conditions: a systematic review and meta-analysis. *JAMA Network Open,* 4**,** e2116382-e2116382.
HOLLENBECK, C., HASKELL, W., ROSENTHAL, M. & REAVEN, G. 1985. Effect of habitual physical activity on regulation of insulin-stimulated glucose disposal in older males. *Journal of the American Geriatrics Society,* 33**,** 273-277.
HOPKINSON, Y., HILL, D. M., FELLOWS, L. & FRYER, S. 2018. Midwives understanding of physical activity guidelines during pregnancy. *Midwifery,* 59**,** 23-26.
HOROWITZ, J. F., MORA-RODRIGUEZ, R., BYERLEY, L. O. & COYLE, E. F. 1997. Lipolytic suppression following carbohydrate ingestion limits fat oxidation during exercise. *American Journal of Physiology-Endocrinology And Metabolism*.
HOWARD, L. M. & KHALIFEH, H. 2020. Perinatal mental health: a review of progress and challenges. *World Psychiatry,* 19**,** 313-327.
ILLSLEY, N. P. 2000. Placental glucose transport in diabetic pregnancy. *Clinical obstetrics and gynecology,* 43**,** 116-126.
INSTITUTE FOR GOVERNMENT 2021. Timeline of UK Government Coronavirus Lockdowns and Measures, March 2020 to December 2021.

IPAQ RESEARCH COMMITTEE 2005. Guidelines for data processing and analysis of the International Physical Activity Questionnaire (IPAQ)-short and long forms. *http://www. ipaq. ki. se/scoring. pdf*.

ISTVAN, J. 1986. Stress, anxiety, and birth outcomes: a critical review of the evidence. *Psychological Bulletin,* 100**,** 331.

JARDE, A., MORAIS, M., KINGSTON, D., GIALLO, R., MACQUEEN, G. M., GIGLIA, L., BEYENE, J., WANG, Y. & MCDONALD, S. D. 2016. Neonatal outcomes in women with untreated antenatal depression compared with women without depression: a systematic review and meta-analysis. *JAMA psychiatry,* 73**,** 826-837.

JARDINE, J., RELPH, S., MAGEE, L. A., VON DADELSZEN, P., MORRIS, E., ROSS-DAVIE, M., DRAYCOTT, T. & KHALIL, A. 2021. Maternity services in the UK during the coronavirus disease 2019 pandemic: a national survey of modifications to standard care. *BJOG: An International Journal of Obstetrics & Gynaecology,* 128**,** 880-889.

JOHNSON, R. & SLADE, P. 2003. Obstetric complications and anxiety during pregnancy: is there a relationship? *Journal of Psychosomatic Obstetrics & Gynecology,* 24**,** 1-14.

JONES, H., GEORGE, K. P., SCOTT, A., BUCKLEY, J. P., WATSON, P. M., OXBOROUGH, D. L., THIJSSEN, D. H., GRAVES, L. E., WHYTE, G. P. & MCGREGOR, G. 2021. Charter to establish clinical exercise physiology as a recognised allied health profession in the UK: a call to action. *BMJ open sport & exercise medicine,* 7**,** e001158.

JUHL, M., MADSEN, M., ANDERSEN, A. M., ANDERSEN, P. & OLSEN, J. 2012. Distribution and predictors of exercise habits among pregnant women in the Danish National Birth Cohort. *Scandinavian journal of medicine & science in sports,* 22**,** 128-138.

JUNG, M., LOCKE, S., BOURNE, J., BEAUCHAMP, M., LEE, T., SINGER, J., MACPHERSON, M., BARRY, J., JONES, C. & LITTLE, J. 2020. Cardiorespiratory fitness and accelerometer-determined physical activity following one year of free-living high-intensity interval training and moderate-intensity continuous training: a randomized trial. *International Journal of Behavioral Nutrition and Physical Activity,* 17**,** 1-10.

KARAVADRA, B., STOCKL, A., PROSSER-SNELLING, E., SIMPSON, P. & MORRIS, E. 2020. Women's perceptions of COVID-19 and their healthcare experiences: a qualitative thematic analysis of a national survey of pregnant women in the United Kingdom. *BMC Pregnancy and Childbirth,* 20**,** 1-8.

KAWAJIRI, M., NAKAMURA, Y., TAKEISHI, Y., ITO, N., ATOGAMI, F. & YOSHIZAWA, T. 2020. Longitudinal study of physical activity using an accelerometer in Japanese pregnant women. *Japan Journal of Nursing Science,* 17**,** e12294.

KHALIL, A., VON DADELSZEN, P., KALAFAT, E., SEBGHATI, M., LADHANI, S., UGWUMADU, A., DRAYCOTT, T., O'BRIEN, P. & MAGEE, L. 2021. Change in obstetric attendance and activities during the COVID-19 pandemic. *The Lancet Infectious Diseases,* 21**,** e115.

KHAYLIS, A., YIASLAS, T., BERGSTROM, J. & GORE-FELTON, C. 2010. A review of efficacious technology-based weight-loss interventions: five key components. *Telemedicine and e-Health,* 16**,** 931-938.

KING, A. C., HEKLER, E. B., GRIECO, L. A., WINTER, S. J., SHEATS, J. L., BUMAN, M. P., BANERJEE, B., ROBINSON, T. N. & CIRIMELE, J. 2016. Effects of three motivationally targeted mobile device applications on initial physical activity and sedentary behavior change in midlife and older adults: a randomized trial. *PloS one,* 11**,** e0156370.

KJOS, S. L., HENRY, O., LEE, R. M., BUCHANAN, T. A. & MISHELL JR, D. R. 1993. The effect of lactation on glucose and lipid metabolism in women with recent gestational diabetes. *Obstetrics and gynecology,* 82**,** 451-455.
KLEPIN, K., WING, D., HIGGINS, M., NICHOLS, J. & GODINO, J. G. 2019. Validity of cardiorespiratory fitness measured with fitbit compared to V˙ O2max. *Medicine and Science in Sports and Exercise,* 51**,** 2251.
KNIGHT, M., BUNCH, K., CAIRNS, A., CANTWELL, R., COX, P. & KEYNON, S. 2020. Saving lives, improving mothers' care. Rapid report: learning from SARS-CoV-2-related and associated maternal deaths in the UK. *University of Oxford: Oxford: National Perinatal Epidemiology Unit*.
KOHL III, H. W., CRAIG, C. L., LAMBERT, E. V., INOUE, S., ALKANDARI, J. R., LEETONGIN, G., KAHLMEIER, S. & GROUP, L. P. A. S. W. 2012. The pandemic of physical inactivity: global action for public health. *The lancet,* 380**,** 294-305.
KOŁOMAŃSKA, D., ZARAWSKI, M. & MAZUR-BIALY, A. 2019. Physical activity and depressive disorders in pregnant women—A systematic review. *Medicina,* 55**,** 212.
KOOIMAN, T. J., DONTJE, M. L., SPRENGER, S. R., KRIJNEN, W. P., VAN DER SCHANS, C. P. & DE GROOT, M. 2015. Reliability and validity of ten consumer activity trackers. *BMC sports science, medicine and rehabilitation,* 7**,** 1-11.
KRANS, E. E. & CHANG, J. C. 2011. A will without a way: barriers and facilitators to exercise during pregnancy of low-income, African American women. *Women & health,* 51**,** 777-794.
KRISTENSEN, K., ÖGGE, L. E., SENGPIEL, V., KJÖLHEDE, K., DOTEVALL, A., ELFVIN, A., KNOP, F. K., WIBERG, N., KATSAROU, A. & SHAAT, N. 2019. Continuous glucose monitoring in pregnant women with type 1 diabetes: an observational cohort study of 186 pregnancies. *Diabetologia,* 62**,** 1143-1153.
KROENKE, K., SPITZER, R. L. & WILLIAMS, J. B. 2001. The PHQ-9: validity of a brief depression severity measure. *Journal of general internal medicine,* 16**,** 606-613.
KRZEPOTA, J., SADOWSKA, D. & BIERNAT, E. 2018. Relationships between physical activity and quality of life in pregnant women in the second and third trimester. *International journal of environmental research and public health,* 15**,** 2745.
LAIN, K. Y. & CATALANO, P. M. 2007. Metabolic changes in pregnancy. *Clinical obstetrics and gynecology,* 50**,** 938-948.
LAKER, R. C., LILLARD, T. S., OKUTSU, M., ZHANG, M., HOEHN, K. L., CONNELLY, J. J. & YAN, Z. 2014. Exercise prevents maternal high-fat diet–induced hypermethylation of the Pgc-1α gene and age-dependent metabolic dysfunction in the offspring. *Diabetes,* 63**,** 1605-1611.
LAW, G. R., ELLISON, G. T., SECHER, A. L., DAMM, P., MATHIESEN, E. R., TEMPLE, R., MURPHY, H. R. & SCOTT, E. M. 2015. Analysis of continuous glucose monitoring in pregnant women with diabetes: distinct temporal patterns of glucose associated with large-for-gestational-age infants. *Diabetes Care,* 38**,** 1319-1325.
LEBEL, C., MACKINNON, A., BAGSHAWE, M., TOMFOHR-MADSEN, L. & GIESBRECHT, G. 2020. Elevated depression and anxiety symptoms among pregnant individuals during the COVID-19 pandemic. *Journal of affective disorders,* 277**,** 5-13.
LEE, A. M., LAM, S. K., LAU, S. M. S. M., CHONG, C. S. Y., CHUI, H. W. & FONG, D. Y. T. 2007. Prevalence, course, and risk factors for antenatal anxiety and depression. *Obstetrics & Gynecology,* 110**,** 1102-1112.
LEE, D.-C., ARTERO, E. G., SUI, X. & BLAIR, S. N. 2010. Mortality trends in the general population: the importance of cardiorespiratory fitness. *Journal of psychopharmacology,* 24**,** 27-35.

LEE, I.-M., SHIROMA, E. J., LOBELO, F., PUSKA, P., BLAIR, S. N., KATZMARZYK, P. T. & GROUP, L. P. A. S. W. 2012. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *The lancet,* 380**,** 219-229.
LEIFERMAN, J., SWIBAS, T., KOINESS, K., MARSHALL, J. A. & DUNN, A. L. 2011. My baby, my move: examination of perceived barriers and motivating factors related to antenatal physical activity. *Journal of midwifery & women's health,* 56**,** 33-40.
LEIGH, B. & MILGROM, J. 2008. Risk factors for antenatal depression, postnatal depression and parenting stress. *BMC psychiatry,* 8**,** 1-11.
LEPPÄNEN, M., AITTASALO, M., RAITANEN, J., KINNUNEN, T. I., KUJALA, U. M. & LUOTO, R. 2014. Physical activity during pregnancy: predictors of change, perceived support and barriers among women at increased risk of gestational diabetes. *Maternal and child health journal,* 18**,** 2158-2166.
LI, D., LIU, L. & ODOULI, R. 2009. Presence of depressive symptoms during early pregnancy and the risk of preterm delivery: a prospective cohort study. *Human reproduction,* 24**,** 146-153.
LIND, T., BILLEWICZ, W. & BROWN, G. 1973. A serial study of changes occurring in the oral glucose tolerance test during pregnancy. *BJOG: An International Journal of Obstetrics & Gynaecology,* 80**,** 1033-1039.
LITTLETON, H. L., BREITKOPF, C. R. & BERENSON, A. B. 2007. Correlates of anxiety symptoms during pregnancy and association with perinatal outcomes: a meta-analysis. *American journal of obstetrics and gynecology,* 196**,** 424-432.
LIU, N., GOU, W.-H., WANG, J., CHEN, D.-D., SUN, W.-J., GUO, P.-P., ZHANG, X.-H. & ZHANG, W. 2019. Effects of exercise on pregnant women's quality of life: A systematic review. *European Journal of Obstetrics & Gynecology and Reproductive Biology,* 242**,** 170-177.
LOCKE, S. R., BOURNE, J. E., BEAUCHAMP, M. R., LITTLE, J. P., BARRY, J., SINGER, J. & JUNG, M. E. 2018. High-Intensity Interval or Continuous Moderate Exercise: A 24-Week Pilot Trial. *Med Sci Sports Exerc,* 50**,** 2067-2075.
LUO, Y. & YIN, K. 2020. Management of pregnant women infected with COVID-19. *The Lancet Infectious Diseases,* 20**,** 513-514.
MANSON, J. E., GREENLAND, P., LACROIX, A. Z., STEFANICK, M. L., MOUTON, C. P., OBERMAN, A., PERRI, M. G., SHEPS, D. S., PETTINGER, M. B. & SISCOVICK, D. S. 2002. Walking compared with vigorous exercise for the prevention of cardiovascular events in women. *New England journal of medicine,* 347**,** 716-725.
MARQUEZ, D. X., BUSTAMANTE, E. E., BOCK, B. C., MARKENSON, G., TOVAR, A. & CHASAN-TABER, L. 2009. Perspectives of Latina and non-Latina white women on barriers and facilitators to exercise in pregnancy. *Women & health,* 49**,** 505-521.
MAY, L. E., ALLEN, J. J. & GUSTAFSON, K. M. 2016. Fetal and maternal cardiac responses to physical activity and exercise during pregnancy. *Early Hum Dev,* 94**,** 49-52.
MAY, L. E., GLAROS, A., YEH, H. W., CLAPP, J. F., 3RD & GUSTAFSON, K. M. 2010. Aerobic exercise during pregnancy influences fetal cardiac autonomic control of heart rate and heart rate variability. *Early Hum Dev,* 86**,** 213-7.
MAY, L. E., SCHOLTZ, S. A., SUMINSKI, R. & GUSTAFSON, K. M. 2014. Aerobic exercise during pregnancy influences infant heart rate variability at one month of age. *Early Hum Dev,* 90**,** 33-8.
MAY, L. E., SUMINSKI, R. R., LANGAKER, M. D., YEH, H. W. & GUSTAFSON, K. M. 2012. Regular maternal exercise dose and fetal heart outcome. *Med Sci Sports Exerc,* 44**,** 1252-8.

MCCARTHY, H., POTTS, H. W. & FISHER, A. 2021. Physical activity behavior before, during, and after COVID-19 restrictions: longitudinal smartphone-tracking study of adults in the United Kingdom. *Journal of medical Internet research,* 23**,** e23701.

MCLEISH, J. & REDSHAW, M. 2017. Mothers' accounts of the impact on emotional wellbeing of organised peer support in pregnancy and early parenthood: a qualitative study. *BMC pregnancy and childbirth,* 17**,** 1-14.

MEAH, V. L., DAVIES, G. A. & DAVENPORT, M. H. 2020. Why can't I exercise during pregnancy? Time to revisit medical 'absolute'and 'relative'contraindications: systematic review of evidence of harm and a call to action. *British Journal of Sports Medicine,* 54**,** 1395-1404.

MELENDER, H. L. & LAURI, S. 2002. Experiences of security associated with pregnancy and childbirth: a study of pregnant women. *International journal of nursing practice,* 8**,** 289-296.

METZGER, B. E. 2007. Long-term outcomes in mothers diagnosed with gestational diabetes mellitus and their offspring. *Clinical obstetrics and gynecology,* 50**,** 972-979.

MIKINES, K. J., SONNE, B., FARRELL, P., TRONIER, B. & GALBO, H. 1988. Effect of physical exercise on sensitivity and responsiveness to insulin in humans. *American Journal of Physiology-Endocrinology And Metabolism,* 254**,** E248-E259.

MILLS, J. L., JOVANOVIC, L., KNOPP, R., AARONS, J., CONLEY, M., PARK, E., LEE, Y. J., HOLMES, L., SIMPSON, J. L. & METZGER, B. 1998. Physiological reduction in fasting plasma glucose concentration in the first trimester of normal pregnancy: the diabetes in early pregnancy study. *Metabolism,* 47**,** 1140-1144.

MINISTRY OF HOUSING COMMUNITIES & LOCAL GOVERNMENT. 2015. *English Indices of Deprivation 2015* [Online]. Government Official Statistics,. Available: https://www.gov.uk/government/statistics/english-indices-of-deprivation-2015 [Accessed 02/02/2022].

MOTTOLA, M. & CHRISTOPHER, P. 1991. Effects of maternal exercise on liver and skeletal muscle glycogen storage in pregnant rats. *Journal of Applied Physiology,* 71**,** 1015-1019.

MOTTOLA, M. F. & ARTAL, R. 2016. Role of exercise in reducing gestational diabetes mellitus. *Clinical obstetrics and gynecology,* 59**,** 620-628.

MOTTOLA, M. F., DAVENPORT, M. H., RUCHAT, S.-M., DAVIES, G. A., POITRAS, V. J., GRAY, C. E., GARCIA, A. J., BARROWMAN, N., ADAMO, K. B. & DUGGAN, M. 2018. 2019 Canadian guideline for physical activity throughout pregnancy. *Br J Sports Med,* 52**,** 1339-1346.

MOTTOLA, M. F., INGLIS, S., BRUN, C. R. & HAMMOND, J.-A. 2013. Physiological and metabolic responses of late pregnant women to 40 min of steady-state exercise followed by an oral glucose tolerance perturbation. *Journal of Applied Physiology,* 115**,** 597-604.

MOURADY, D., RICHA, S., KARAM, R., PAPAZIAN, T., HAJJ MOUSSA, F., EL OSTA, N., KESROUANI, A., AZOURI, J., JABBOUR, H. & HAJJ, A. 2017. Associations between quality of life, physical activity, worry, depression and insomnia: A cross-sectional designed study in healthy pregnant women. *PloS one,* 12**,** e0178181.

MURPHY, H. R. 2019. Continuous glucose monitoring targets in type 1 diabetes pregnancy: every 5% time in range matters. *Diabetologia,* 62**,** 1123-1128.

NAKRANI, M. N., WINELAND, R. H. & ANJUM, F. 2020. Physiology, Glucose Metabolism. *StatPearls [Internet]*.

NATIONAL INSTITUTE OF DIABETES AND DIGESTIVE AND KIDNEY DISEASES. 2014. *Sickle Cell Trait & Other Hemoglobinopathies & Diabetes (For Providers)* [Online].

Available: https://www.niddk.nih.gov/health-information/professionals/clinical-tools-patient-management/diabetes/sickle-cell-trait-hemoglobinopathies-diabetes [Accessed 04/02 2021].

NATIONAL INSTITUTES OF HEALTH 2015. Consideration of Sex as a Biological Variable in NIH-funded Research.

NIELSEN, L. R., EKBOM, P., DAMM, P., GLÜMER, C., FRANDSEN, M. M., JENSEN, D. M. & MATHIESEN, E. R. 2004. HbA_{1c} Levels Are Significantly Lower in Early and Late Pregnancy. *Diabetes Care,* 27**,** 1200-1201.

NIEMI, M., FALKENBERG, T., PETZOLD, M., CHUC, N. T. K. & PATEL, V. 2013. Symptoms of antenatal common mental disorders, preterm birth and low birthweight: a prospective cohort study in a semi-rural district of V ietnam. *Tropical Medicine & International Health,* 18**,** 687-695.

NOONAN, D. & SIMMONS, L. A. 2021. Navigating nonessential research trials during COVID19: the push we needed for using digital technology to increase access for rural participants? *The Journal of rural health: official journal of the American Rural Health Association and the National Rural Health Care Association,* 37**,** 185.

O'CONNOR, T. G., HERON, J., GOLDING, J., BEVERIDGE, M. & GLOVER, V. 2002. Maternal antenatal anxiety and children's behavioural/emotional problems at 4 years: Report from the Avon Longitudinal Study of Parents and Children. *The British Journal of Psychiatry,* 180**,** 502-508.

OKUNO, S., AKAZAWO, S., YASUHI, I., KAWASAKI, E., MATSUMOTO, K., YAMASAKI, H., MATSUO, H., YAMAGUCHI, Y. & NAGATAKI, S. 1995. Decreased expression of the GLUT4 glucose transporter protein in adipose tissue during pregnancy. *Hormone and metabolic research,* 27**,** 231-234.

OLANDER, E. K., ATKINSON, L., EDMUNDS, J. K. & FRENCH, D. P. 2011. The views of pre- and post-natal women and health professionals regarding gestational weight gain: An exploratory study. *Sexual & Reproductive Healthcare,* 2**,** 43-48.

OVERDIJKINK, S. B., VELU, A. V., ROSMAN, A. N., VAN BEUKERING, M. D., KOK, M. & STEEGERS-THEUNISSEN, R. P. 2018. The usability and effectiveness of mobile health technology–based lifestyle and medical intervention apps supporting health care during pregnancy: systematic review. *JMIR mHealth and uHealth,* 6**,** e8834.

OWE, K. M., NYSTAD, W. & BØ, K. 2009. Correlates of regular exercise during pregnancy: the Norwegian Mother and Child Cohort Study. *Scandinavian journal of medicine & science in sports,* 19**,** 637-645.

PAARLBERG, K. M., VINGERHOETS, A. J., PASSCHIER, J., DEKKER, G. A. & VAN GEIJN, H. P. 1995. Psychosocial factors and pregnancy outcome: a review with emphasis on methodological issues. *Journal of psychosomatic research,* 39**,** 563-595.

PAMPAKA, D., PAPATHEODOROU, S. I., ALSEAIDAN, M., AL WOTAYAN, R., WRIGHT, R. J., BURING, J. E., DOCKERY, D. W. & CHRISTOPHI, C. A. 2021. Antenatal depressive symptoms and adverse perinatal outcomes. *BMC Pregnancy and Childbirth,* 21**,** 1-10.

PARRETTI, E., MECACCI, F., PAPINI, M., CIONI, R., CARIGNANI, L., MIGNOSA, M., LA TORRE, P. & MELLO, G. 2001. Third-trimester maternal glucose levels from diurnal profiles in nondiabetic pregnancies: correlation with sonographic parameters of fetal growth. *Diabetes Care,* 24**,** 1319-1323.

PATTE, R., PRATT, M., BLAIR, S., HASKELL, W., MACERA, C. & BOUCHARD, C. 1995. A recommendation from the Centers for Disease control and Prevention and the American College of Sports Medicine. *JAMA,* 273**,** 402-7.

PEDERSEN, B. & ANDERSEN, L. 2011. Physical activity. Handbook in Prevention and Treatment. *National Board of Health*.

PELLEGRINI, C. A., VERBA, S. D., OTTO, A. D., HELSEL, D. L., DAVIS, K. K. & JAKICIC, J. M. 2012. The comparison of a technology-based system and an in-person behavioral weight loss intervention. *Obesity,* 20**,** 356-363.

PERALES, M., NAGPAL, T. S. & BARAKAT, R. 2019. Physiological Changes During Pregnancy: Main Adaptations, Discomforts, and Implications for Physical Activity and Exercise. *Exercise and Sporting Activity During Pregnancy.* Springer.

PERALES, M., REFOYO, I., COTERON, J., BACCHI, M. & BARAKAT, R. 2015. Exercise during pregnancy attenuates prenatal depression: a randomized controlled trial. *Evaluation & the health professions,* 38**,** 59-72.

PEREIRA, M. A., RIFAS-SHIMAN, S. L., KLEINMAN, K. P., RICH-EDWARDS, J. W., PETERSON, K. E. & GILLMAN, M. W. 2007. Predictors of change in physical activity during and after pregnancy: Project Viva. *American journal of preventive medicine,* 32**,** 312-319.

PETROVIC, D., PEROVIC, M., LAZOVIC, B. & PANTIC, I. 2016. Association between walking, dysphoric mood and anxiety in late pregnancy: A cross-sectional study. *Psychiatry research,* 246**,** 360-363.

POMEROY, J., RENSTRÖM, F., GRADMARK, A. M., MOGREN, I., PERSSON, M., BLUCK, L., WRIGHT, A., KAHN, S. E., DOMELLÖF, M. & FRANKS, P. W. 2013. Maternal physical activity and insulin action in pregnancy and their relationships with infant body composition. *Diabetes care,* 36**,** 267-269.

POUDEVIGNE, M. S. & O'CONNOR, P. J. 2006. A review of physical activity patterns in pregnant women and their relationship to psychological health. *Sports medicine,* 36**,** 19-38.

PREIS, H., LOBEL, M. & BENYAMINI, Y. 2019. Between expectancy and experience: testing a model of childbirth satisfaction. *Psychology of Women Quarterly,* 43**,** 105-117.

PREIS, H., MAHAFFEY, B., PATI, S., HEISELMAN, C. & LOBEL, M. 2021. Adverse perinatal outcomes predicted by prenatal maternal stress among US women at the COVID-19 pandemic onset. *Annals of Behavioral Medicine,* 55**,** 179-191.

PRINCE, S. A., ADAMO, K. B., HAMEL, M. E., HARDT, J., GORBER, S. C. & TREMBLAY, M. 2008. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *International journal of behavioral nutrition and physical activity,* 5**,** 1-24.

PRUETT, E. D. & OSEID, S. 1970. Effect of exercise on glucose and insulin response to glucose infusion. *Scandinavian journal of clinical and laboratory investigation,* 26**,** 277-285.

RAIPURIA, M., BAHARI, H. & MORRIS, M. J. 2015. Effects of maternal diet and exercise during pregnancy on glucose metabolism in skeletal muscle and fat of weanling rats. *PloS one,* 10**,** e0120980.

RAMOS-LEVÍ, A. M., PÉREZ-FERRE, N., FERNÁNDEZ, M. D., DEL VALLE, L., BORDIU, E., BEDIA, A. R., HERRAIZ, M. A., TORREJÓN, M. J. & CALLE-PASCUAL, A. L. 2012. Risk factors for gestational diabetes mellitus in a large population of women living in Spain: implications for preventative strategies. *International journal of endocrinology,* 2012.

RAUFF, E. L. & DOWNS, D. S. 2011. Mediating effects of body image satisfaction on exercise behavior, depressive symptoms, and gestational weight gain in pregnancy. *Annals of behavioral medicine,* 42**,** 381-390.

REDSHAW, M. & HENDERSON, J. 2013. From antenatal to postnatal depression: associated factors and mitigating influences. *Journal of women's health,* 22**,** 518-525.

REECE, E. A. 2010. The fetal and maternal consequences of gestational diabetes mellitus. *The journal of maternal-fetal & neonatal medicine,* 23**,** 199-203.

REIJONSAARI, K., VEHTARI, A., KAHILAKOSKI, O.-P., VAN MECHELEN, W., ARO, T. & TAIMELA, S. 2012. The effectiveness of physical activity monitoring and distance counseling in an occupational setting–Results from a randomized controlled trial (CoAct). *BMC Public Health,* 12**,** 1-10.

RICHTER, E. A. & HARGREAVES, M. 2013. Exercise, GLUT4, and skeletal muscle glucose uptake. *Physiological reviews*.

RILEY, T., SULLY, E., AHMED, Z. & BIDDLECOM, A. 2020. Estimates of the potential impact of the COVID-19 pandemic on sexual and reproductive health in low-and middle-income countries. *International Perspectives on Sexual and Reproductive Health,* 46**,** 73-76.

RISKIN-MASHIAH, S., DAMTI, A., YOUNES, G. & AUSLANDER, R. 2011. Normal fasting plasma glucose levels during pregnancy: a hospital-based study. *J Perinat Med,* 39**,** 209-11.

RITCHIE, J., LEWIS, J., ELAM, G., TENNANT, R., RAHIM, N. 2014. Designing and selecting samples. *In:* RITCHIE, J., LEWIS, J., MCNAUGHTON NICHOLLS, C., ORMSTON, R. (ed.) *Qualitative Research Practice.* Sage.

RITCHIE, J. & SPENCER, L. 2002. Qualitative data analysis for applied policy research. *The qualitative researcher's companion,* 573**,** 305-29.

ROBERTON, T., CARTER, E. D., CHOU, V. B., STEGMULLER, A. R., JACKSON, B. D., TAM, Y., SAWADOGO-LEWIS, T. & WALKER, N. 2020. Early estimates of the indirect effects of the COVID-19 pandemic on maternal and child mortality in low-income and middle-income countries: a modelling study. *The Lancet Global Health,* 8**,** e901-e908.

ROBERTSON, E., GRACE, S., WALLINGTON, T. & STEWART, D. E. 2004. Antenatal risk factors for postpartum depression: a synthesis of recent literature. *General hospital psychiatry,* 26**,** 289-295.

ROBLEDO-COLONIA, A. F., SANDOVAL-RESTREPO, N., MOSQUERA-VALDERRAMA, Y. F., ESCOBAR-HURTADO, C. & RAMÍREZ-VÉLEZ, R. 2012. Aerobic exercise training during pregnancy reduces depressive symptoms in nulliparous women: a randomised trial. *Journal of physiotherapy,* 58**,** 9-15.

RODBARD, D. 2016. Continuous glucose monitoring: a review of successes, challenges, and opportunities. *Diabetes technology & therapeutics,* 18**,** S2-3-S2-13.

ROTH, M. A. & MINDELL, J. S. 2013. Who provides accelerometry data? Correlates of adherence to wearing an accelerometry motion sensor: the 2008 Health Survey for England. *Journal of Physical Activity and Health,* 10**,** 70-78.

ROY, M., WILLIAMS, S. M., BROWN, R. C., MEREDITH-JONES, K. A., OSBORNE, H., JOSPE, M. & TAYLOR, R. W. 2018. HIIT in the real world: outcomes from a 12-month intervention in overweight adults. *Med Sci Sports Exerc,* 50**,** 1818-26.

RYAN, E. A., O'SULLIVAN, M. J. & SKYLER, J. S. 1985. Insulin action during pregnancy: studies with the euglycemic clamp technique. *Diabetes,* 34**,** 380-389.

SACCONE, G., FLORIO, A., AIELLO, F., VENTURELLA, R., DE ANGELIS, M. C., LOCCI, M., BIFULCO, G., ZULLO, F. & SARDO, A. D. S. 2020. Psychological impact of coronavirus disease 2019 in pregnant women. *American Journal of Obstetrics & Gynecology,* 223**,** 293-295.

SACKS, D. A., GREENSPOON, J. S., ABU-FADIL, S., HENRY, H. M., WOLDE-TSADIK, G. & YAO, J. F. 1995. Toward universal criteria for gestational diabetes: the 75-gram glucose tolerance test in pregnancy. *American journal of obstetrics and gynecology,* 172**,** 607-614.

SALKIND, S. J., HUIZENGA, R., FONDA, S. J., WALKER, M. S. & VIGERSKY, R. A. 2014. Glycemic variability in nondiabetic morbidly obese persons: results of an observational study and review of the literature. *Journal of diabetes science and technology,* 8**,** 1042-1047.

SATYAPRIYA, M., NAGARATHNA, R., PADMALATHA, V. & NAGENDRA, H. 2013. Effect of integrated yoga on anxiety, depression & well being in normal pregnancy. *Complementary therapies in clinical practice,* 19**,** 230-236.

SCHNELL, O., CROCKER, J. B. & WENG, J. 2017. Impact of HbA1c testing at point of care on diabetes management. *Journal of diabetes science and technology,* 11**,** 611-617.

SCHREUDER, Y. J., HUTTEN, B. A., VAN EIJSDEN, M., JANSEN, E. H., VISSERS, M. N., TWICKLER, M. T. & VRIJKOTTE, T. G. 2011. Ethnic differences in maternal total cholesterol and triglyceride levels during pregnancy: the contribution of demographics, behavioural factors and clinical characteristics. *European journal of clinical nutrition,* 65**,** 580-589.

SCOTT, S. D., ROTTER, T., FLYNN, R., BROOKS, H. M., PLESUK, T., BANNAR-MARTIN, K. H., CHAMBERS, T. & HARTLING, L. 2019. Systematic review of the use of process evaluations in knowledge translation research. *Systematic reviews,* 8**,** 1-10.

SCOTT, S. N., SHEPHERD, S. O., STRAUSS, J. A., WAGENMAKERS, A. J. & COCKS, M. 2020. Home-based high-intensity interval training reduces barriers to exercise in people with type 1 diabetes. *Experimental physiology,* 105**,** 571-578.

SEAQUIST, E. R., ANDERSON, J., CHILDS, B., CRYER, P., DAGOGO-JACK, S., FISH, L., HELLER, S. R., RODRIGUEZ, H., ROSENZWEIG, J. & VIGERSKY, R. 2013. Hypoglycemia and diabetes: a report of a workgroup of the American Diabetes Association and the Endocrine Society. *The Journal of Clinical Endocrinology & Metabolism,* 98**,** 1845-1859.

SHEFFIELD, K. M. & WOODS-GISCOMBÉ, C. L. 2016. Efficacy, feasibility, and acceptability of perinatal yoga on women's mental health and well-being: a systematic literature review. *Journal of Holistic Nursing,* 34**,** 64-79.

SHELDON, R. D., BLAIZE, A. N., FLETCHER, J. A., PEARSON, K. J., DONKIN, S. S., NEWCOMER, S. C. & RECTOR, R. S. 2016. Gestational exercise protects adult male offspring from high-fat diet-induced hepatic steatosis. *Journal of hepatology,* 64**,** 171-178.

SHIN, D. W., YUN, J. M., SHIN, J. H., KWON, H., MIN, H. Y., JOH, H. K., CHUNG, W. J., PARK, J. H., JUNG, K. T. & CHO, B. 2017. Enhancing physical activity and reducing obesity through smartcare and financial incentives: a pilot randomized trial. *Obesity,* 25**,** 302-310.

SHUGER, S. L., BARRY, V. W., SUI, X., MCCLAIN, A., HAND, G. A., WILCOX, S., MERIWETHER, R. A., HARDIN, J. W. & BLAIR, S. N. 2011. Electronic feedback in a diet-and physical activity-based lifestyle intervention for weight loss: a randomized controlled trial. *International Journal of Behavioral Nutrition and Physical Activity,* 8**,** 1-8.

SIEGMUND, T., RAD, N. T., RITTERATH, C., SIEBERT, G., HENRICH, W. & BUHLING, K. J. 2008. Longitudinal changes in the continuous glucose profile measured by the CGMS® in healthy pregnant women and determination of cut-off values. *European Journal of Obstetrics & Gynecology and Reproductive Biology,* 139**,** 46-52.

SIMPSON, W., GLAZER, M., MICHALSKI, N., STEINER, M. & FREY, B. N. 2014. Comparative efficacy of the generalized anxiety disorder 7-item scale and the Edinburgh Postnatal Depression Scale as screening tools for generalized anxiety disorder in pregnancy and the postpartum period. *The Canadian Journal of Psychiatry,* 59**,** 434-440.

SKOW, R. J., KING, E. C., STEINBACK, C. D. & DAVENPORT, M. H. 2017. The influence of prenatal exercise and pre-eclampsia on maternal vascular function. *Clin Sci (Lond),* 131**,** 2223-2240.

SPITZER, R. L., KROENKE, K., WILLIAMS, J. B. & LÖWE, B. 2006. A brief measure for assessing generalized anxiety disorder: the GAD-7. *Archives of internal medicine,* 166**,** 1092-1097.

SPORT ENGLAND 2020. COVID-19 briefing: exploring attitudes and behaviours in England during the COVID-19 pandemic. *Sport England: London, UK*.

SPORT ENGLAND 2021. Active Lives Adult Survey November 2020-21 Report.

STAMPINI, V., MONZANI, A., CARISTIA, S., FERRANTE, G., GERBINO, M., DE PEDRINI, A., AMADORI, R., RABBONE, I. & SURICO, D. 2021. The perception of Italian pregnant women and new mothers about their psychological wellbeing, lifestyle, delivery, and neonatal management experience during the COVID-19 pandemic lockdown: a web-based survey. *BMC pregnancy and childbirth,* 21**,** 1-12.

STANFORD, K. I., LEE, M.-Y., GETCHELL, K. M., SO, K., HIRSHMAN, M. F. & GOODYEAR, L. J. 2015. Exercise before and during pregnancy prevents the deleterious effects of maternal high-fat feeding on metabolic health of male offspring. *Diabetes,* 64**,** 427-433.

STANFORD, K. I., TAKAHASHI, H., SO, K., ALVES-WAGNER, A. B., PRINCE, N. B., LEHNIG, A. C., GETCHELL, K. M., LEE, M.-Y., HIRSHMAN, M. F. & GOODYEAR, L. J. 2017. Maternal exercise improves glucose tolerance in female offspring. *Diabetes,* 66**,** 2124-2136.

STATISTA. 2021. *Number of Wearable Device Users in the United States from 2014 to 2022* [Online]. Lionel Sujay Vailshery. Available: https://www.statista.com/statistics/543070/number-of-wearable-users-in-the-us/ [Accessed 24/01/2022].

STRAUB, H., ADAMS, M., KIM, J. J. & SILVER, R. K. 2012. Antenatal depressive symptoms increase the likelihood of preterm birth. *American journal of obstetrics and gynecology,* 207**,** 329. e1-329. e4.

STUBBS, B., VANCAMPFORT, D., ROSENBAUM, S., WARD, P. B., RICHARDS, J., SOUNDY, A., VERONESE, N., SOLMI, M. & SCHUCH, F. B. 2016. Dropout from exercise randomized controlled trials among people with depression: a meta-analysis and meta regression. *Journal of affective disorders,* 190**,** 457-466.

SWINDELL, N., MACKINTOSH, K., MCNARRY, M., STEPHENS, J. W., SLUIK, D., FOGELHOLM, M., DRUMMEN, M., MACDONALD, I., MARTINEZ, J. A. & HANDJIEVA-DARLENSKA, T. 2018. Objectively measured physical activity and sedentary time are associated with cardiometabolic risk factors in adults with prediabetes: the PREVIEW study. *Diabetes care,* 41**,** 562-569.

SZEGDA, K., BERTONE-JOHNSON, E. R., PEKOW, P., POWERS, S., MARKENSON, G., DOLE, N. & CHASAN-TABER, L. 2017. Depression during pregnancy and adverse birth outcomes among predominantly Puerto Rican women. *Maternal and child health journal,* 21**,** 942.

TANIGUCHI, C. & SATO, C. 2016. Home-based walking during pregnancy affects mood and birth outcomes among sedentary women: A randomized controlled trial. *International journal of nursing practice,* 22**,** 420-426.

TARNOPOLSKY, M. A. & RUBY, B. C. 2001. Sex differences in carbohydrate metabolism. *Curr Opin Clin Nutr Metab Care,* 4**,** 521-6.

THOMAS, J. G. & BOND, D. S. 2014. Review of innovations in digital health technology to promote weight control. *Current diabetes reports,* 14**,** 485.

THOMPSON, D., BERGER, H., FEIG, D., GAGNON, R., KADER, T., KEELY, E., KOZAK, S., RYAN, E., SERMER, M. & VINOKUROFF, C. 2013. Diabetes and pregnancy. *Can J Diabetes,* 37 Suppl 1**,** S168-83.

THOMPSON, W. G., KUHLE, C. L., KOEPP, G. A., MCCRADY-SPITZER, S. K. & LEVINE, J. A. 2014. "Go4Life" exercise counseling, accelerometer feedback, and activity levels in older people. *Archives of gerontology and geriatrics,* 58**,** 314-319.

TROIANO, R. P., BERRIGAN, D., DODD, K. W., MASSE, L. C., TILERT, T. & MCDOWELL, M. 2008. Physical activity in the United States measured by accelerometer. *Medicine and science in sports and exercise,* 40**,** 181.

TUOMILEHTO, J., LINDSTRÖM, J., ERIKSSON, J. G., VALLE, T. T., HÄMÄLÄINEN, H., ILANNE-PARIKKA, P., KEINÄNEN-KIUKAANNIEMI, S., LAAKSO, M., LOUHERANTA, A. & RASTAS, M. 2001. Prevention of type 2 diabetes mellitus by changes in lifestyle among subjects with impaired glucose tolerance. *New England Journal of Medicine,* 344**,** 1343-1350.

UK CHIEF MEDICAL OFFICERS 2017. UK Chief Medical Officers Recommendations 2017: Physical Activity in Pregnancy.

UNGER, J. M., MOSELEY, A., SYMINGTON, B., CHAVEZ-MACGREGOR, M., RAMSEY, S. D. & HERSHMAN, D. L. 2018. Geographic distribution and survival outcomes for rural patients with cancer treated in clinical trials. *JAMA network open,* 1**,** e181235-e181235.

VAN BALLEGOOIJEN, A. J., VAN DER PLOEG, H. P. & VISSER, M. 2019. Daily sedentary time and physical activity as assessed by accelerometry and their correlates in older adults. *European Review of Aging and Physical Activity,* 16**,** 1-12.

VAN HOYE, K., BOEN, F. & LEFEVRE, J. 2015. The impact of different degrees of feedback on physical activity levels: a 4-week intervention study. *International Journal of Environmental Research and Public Health,* 12**,** 6561-6581.

VANCAMPFORT, D., ROSENBAUM, S., SCHUCH, F. B., WARD, P. B., PROBST, M. & STUBBS, B. 2016. Prevalence and predictors of treatment dropout from physical activity interventions in schizophrenia: a meta-analysis. *General hospital psychiatry,* 39**,** 15-23.

VARGAS-TERRONES, M., BARAKAT, R., SANTACRUZ, B., FERNANDEZ-BUHIGAS, I. & MOTTOLA, M. F. 2019. Physical exercise programme during pregnancy decreases perinatal depression risk: a randomised controlled trial. *British journal of sports medicine,* 53**,** 348-353.

VICTOR, A. 1974. Normal blood sugar variation during pregnancy. *Acta obstetricia et gynecologica Scandinavica,* 53**,** 37-40.

WALSH, J. M., MCGOWAN, C., BYRNE, J. & MCAULIFFE, F. M. 2011. Prevalence of physical activity among healthy pregnant women in Ireland. *International Journal of Gynecology & Obstetrics,* 114**,** 154-155.

WANG, C., LV, L., YANG, Y., CHEN, D., LIU, G., CHEN, L., SONG, Y., HE, L., LI, X. & TIAN, H. 2012. Glucose fluctuations in subjects with normal glucose tolerance, impaired glucose regulation and newly diagnosed type 2 diabetes mellitus. *Clinical endocrinology,* 76**,** 810-815.

WANG, L., KROENKE, K., STUMP, T. E. & MONAHAN, P. O. 2020. Screening for perinatal depression with the patient health questionnaire depression scale (PHQ-9): A systematic review and meta-analysis. *General Hospital Psychiatry*.

WANG, X., PATTERSON, B. W., SMITH, G. I., KAMPELMAN, J., REEDS, D. N., SULLIVAN, S. A. & MITTENDORFER, B. 2013. A∼ 60-min brisk walk increases insulin-stimulated glucose disposal but has no effect on hepatic and adipose tissue insulin sensitivity in older women. *Journal of applied physiology,* 114**,** 1563-1568.

WANG, Y.-M., ZHAO, L.-H., SU, J.-B., QIAO, H.-F., WANG, X.-H., XU, F., CHEN, T., CHEN, J.-F., WU, G. & WANG, X.-Q. 2015. Glycemic variability in normal glucose tolerance women with the previous gestational diabetes mellitus. *Diabetology & metabolic syndrome,* 7**,** 1-8.

WORLD HEALTH ORGANISATION. 2020. *Physical Activity* [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/physical-activity [Accessed 17/12/21].

WORLD HEALTH ORGANIZATION 2019. *Global action plan on physical activity 2018-2030: more active people for a healthier world*, World Health Organization.

YAMADA, M., OKADA, S., ODA, H., NAKAJIMA, Y., BASTIE, C. C., KASAI, Y., OSAKI, A., SHIMODA, Y., SHIBUSAWA, R. & UEHARA, R. 2020. Evaluation of the relationship between glycated hemoglobin A1c and mean glucose levels derived from the professional continuous flash glucose monitoring system. *Endocrine journal,* 67**,** 531-536.

YOGEV, Y., BEN-HAROUSH, A., CHEN, R., ROSENN, B., HOD, M. & LANGER, O. 2004. Diurnal glycemic profile in obese and normal weight nondiabetic pregnant women. *American journal of obstetrics and gynecology,* 191**,** 949-953.

YOUNG, L., BARNASON, S. & DO, V. 2015. Review strategies to recruit and retain rural patient participating self-management behavioral trials. *Online journal of rural research and policy,* 10**,** 1.

YUSOF, N. Y. M., ZULKEFLI, N. A. M., MINHAT, H. S. & AHMAD, N. 2020. Predictors of Physical Inactivity Among Antenatal Women: A Systematic Review. *Malaysian Journal of Medicine and Health Sciences,* 16.

CHAPTER 9: APPENDICIES

Appendix 1. Participant checklist for home-based testing measurements.

YOUR CHECKLIST

Have you...

- ☐ Not eaten for 5 hours
- ☐ Had a glass of water

Do you have everything?

- ☐ Testing booklet
- ☐ Thin, flat object (e.g. a magazine, place mat, iPad)
- ☐ Tape measure
- ☐ Physical activity monitor
- ☐ Scales
- ☐ Blood pressure monitor
- ☐ Bloods kit
- ☐ Flash glucose monitor

INSTRUCTIONS

Refer to the testing booklet for more details on measurements.

Height

1: Do you know your height in cm or feet and inches? If so, enter the measure and skip to #5. ☐

2: With bare feet, stand against a wall. ☐

3: Place flat object on your head and place a mark at the point where the object meets the wall with the sticker provided. ☐

4: Measure the distance from the floor to the sticker with the tape measure. ☐

Weight

5: Place scales on non-carpeted floor and stand on them to measure your weight. ☐

Waist and hip circumference

6: Lift up clothing, then wrap the tape measure around your waist at the level of your belly button. Breathe out and record the result. ☐

7: Take the tape measure and wrap it around the largest part of your hips and record the result. Repeat both waist and hips **3 times.** ☐

Blood pressure

8: Rest for 10 minutes before measuring your blood pressure. ☐

9: Remove any clothing from your upper arm. ☐

10: Wrap the cuff around your upper left arm and place your arm on table or arm rest of a chair ☐

11: Press START/STOP. Be still, don't talk and relax throughout the test. ☐

12: Repeat this **3 times** with one minute rest in between measurements. ☐

RESULTS

Write all your measurements in this box.

Measurements	Results
Height	cm/in
Weight	kg/lbs
Waist Circumference #1	cm/in
Waist Circumference #2	cm/in
Waist Circumference #3	cm/in
Hip Circumference #1	cm/in
Hip Circumference #2	cm/in
Hip Circumference #3	cm/in
Blood Pressure #1	mmHg
Blood Pressure #2	mmHg
Blood Pressure #3	mmHg

Turn over the page to continue the testing...

If at any time, you wish to speak to a member of the research team, please email

M.V.France@2017.ljmu.ac.uk

YOUR CHECKLIST

Refer to the testing booklet for more details on these measurements.

INSTRUCTIONS continued

Blood collection

13: Wash your hands in warm water for 2 minutes, and dry. Have tissue ready to help during collection. ☐

14: Clean your little finger with the alcohol wipe. ☐

15: Twist off the cap from the lancet. ☐

16: Place the lancet on the outside of the little finger & apply pressure until you hear a click and feel a scratch. ☐

17: Wipe the first drop of blood away with some tissue. ☐

18: Massage the side of the hand from the wrist to the finger. As blood droplets form, gently touch them on the inside edge of the collection tube. ☐

19: Fill the collection tube until **500µl**. ☐

20: Replace the lid of the collection tube and invert the tube several times. ☐

21: Clean the finger with tissue and apply pressure, put on a plaster if needed. ☐

22: Place the collection tube back into the plastic clamp shell & seal. ☐

23: Pack the plastic clamp shell into the prepaid envelope and post on the same day. ☐

If at any time, you wish to speak to a member of the research team, please email

M.V.France@2017.ljmu.ac.uk

Glucose monitoring

23: Clean the back of your arm with an alcohol wipe & allow to dry. ☐

24: Unscrew the cap from the grey applicator and open the white sensor. Insert the grey applicator into the white sensor by lining up the dark lines. ☐

25: On a hard surface, press down firmly on the grey applicator until it clicks and comes to a stop. ☐

26: Lift the sensor applicator out of the sensor pack. Be careful not to touch inside the sensor applicator. ☐

27: Place the applicator over the clean area at the back of your arm and push down firmly to apply the sensor to the body. ☐

28: Gently pull the sensor applicator away from your body. Make sure the sensor is secure. **Wear for 7 days.** ☐

29: Scan the sensor with the reader to ensure the sensor is working. If it does not work, please contact us. ☐

Physical activity monitoring

30: Wear the monitor on your non-dominant wrist (e.g. if you're right-handed, wear it on your left) for the next **7 days.** ☐

31: Fit the sitting monitor by following the guidance provided. Make sure it is securely attached and watertight. ☐

32: Post both the Physical Activity Monitors, the diet diary, and Glucose Sensor & Reader, using the prepaid envelope. ☐

Diet diary

33: Record every food and drink that you consume every day for **7 days** including the size of the portion. ☐

34: You can choose to record your diet using the MyFitnessPal app with a study specific email and password if you prefer. ☐

Questionnaires

35: Open the Google Survey link sent to you via email. ☐

36: Complete the questionnaire. ☐

Appendix 2. Topic guide baseline interviews.

Key questions	Probes
- How did you find the resources and training provided before the home testing?	○ How did it help (videos, booklets, checklist, phone call with researcher)
	○ Would you have found it useful for the researcher to be with you during the testing, via video or phone?
	○ Recommendations for improvement
- Did you have any issues receiving the testing package?	
- What did you think about the measures you collected during the scheme?	○ Thoughts on specific outcome measures (questionnaires/bloods/blood pressure etc)
	○ Understanding; interest; comfort; difficulty
	○ Number of measures
	○ Do you think we measured important outcomes?
- What did you think about the 7-day period where you wore the PA monitor and CGM?	○ Activity monitor
	○ Understanding; interest; comfort; difficulty
	○ Number of measures
	○ Do you think we measured what was important? Did we miss anything?
	○ Was it easy to return the monitors to the research team?

Appendix 3. Survey questions post-intervention for mHealth participants.

	Question
1	Did you find any factors particularly helpful in increasing your exercise levels? Please provide up to three facilitators
2	What barriers did you face to increasing your exercise levels? Please provide up to three barriers
3	What did you like about the extra support (e.g., Polar Flow app, fitness watch, counselling sessions and feedback from researcher and HR feedback during exercise)? What could be improved?
4	What did you like about the counselling sessions? What could be improved?
5	What did you like about the text messages? What could be improved?
6	Were there any challenges to accessing or using the participant app? How could these challenges be overcome?
7	Were there any challenges to using the fitness watch? How could these challenges be overcome?
8	Were there any challenges to using the website? How do you think these challenges could be overcome?

Appendix 4. Survey questions post-intervention for online resources participants.

	Questions
1	Did you find any factors particularly helpful in increasing your exercise levels? Please provide up to three facilitators
2	What barriers did you face to increasing your exercise levels? Please provide up to three barriers
3	Were there any challenges to using the website? How do you think these challenges could be overcome?

Appendix 5. Topic guide for semi-structured interviews.

Key questions	Probes
- Can you tell me about your previous experiences of exercise prior to pregnancy?	○ Main barriers and benefits
	○ What impact, if any, do you think your regular occupation has on your overall level of PA?
	○ What did you find difficult about exercise before pregnancy?
- I'd like to move on to talk a bit about your experiences of pregnancy throughout lockdown.. - At what week of pregnancy did you begin self-isolating?	○ What did you find difficult?
	○ How was this experience?
	○ How did lockdown impact daily life?
- What was the main or most difficult change with lockdown?	○ Any difficulties with social connection or isolation?
	○ Changes in occupation, were you able to work from home?
- Thinking about your experiences of lockdown, how did this impact upon your exercise routine and diet?	
- What has your experience of pregnancy throughout lockdown been like overall?	
- Tell me about your experience of healthcare during pregnancy	○ Different to or same as before?
	○ What impact, if any, has this had on your pregnancy experience?
	○ What would you have liked instead/in addition?
- Can you tell me about your perceptions of exercise during pregnancy?	○ In what way do you feel that advice from your midwife/healthcare professionals influence your decision to perform exercise during pregnancy?
	○ Motivation – what is motivating you or could help to motivate you?
	○ Support from family/friends?
	○ What challenges do you forecast for exercising during your pregnancy? How will you overcome these?
	○ Thinking about your previous experiences of exercise, in what way – if at all – do you feel these impact upon your decisions to continue/stop exercise in pregnancy? Have your previous activity levels influenced your

	decision to continue/stop exercise in pregnancy?
- Can you tell me about any goals you might have in mind that you would like to achieve during your pregnancy?	○ Health related/exercise related?
	○ Future intentions post pregnancy?
- Can you tell me about how you are feeling about preparing for labour?	○ Birth plan, any specific preparations (e.g., NCT classes).